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## ONR/ARPA ASSOCIATION

DEVELOPMENT OF A METHOD AND APPARATUS
FOR SPINNING A YARN OF HIGH MODULUS FIBERS*

BY


MYRNE R. RILEY




PROGRAM MANAGER
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10 MYRNE R./RILEY

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## FOREWORD

The research herein was conducted by the staff of the Monsanto/Washington University Association under the sponsorship of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-67-C-0218 (formerly N00014-66-C-0045), ARPA Order No. 876, ONR contract authority NR 356-484/4-13-66, entitled "Development of High Performance Composites."

The prime contractor is Monsanto Research Corporation. The Program Manager is Dr. Rolf Buchdahl (phone 314-694-4721).

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DEVELOPMENT OF A METHOD AND APPARATUS
FOR SPINNING A YARN OF HIGH MODULUS FIBERS*

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St. Louis, Missouri

ABSTRACT

A two-slurry vortex spinning process was developed for spinning a yarn of aligned high modulus core fibers wrapped with helically twisted fibers of the same or lower modulus. Yarn was formed at the entry to the rotating tube of the spinning assembly as the annular fiber suspension twisted around the more viscous core slurry. The rotating tube generated an axial vorticity gradient within the suspension, and the resulting hydrodynamic force twisted the outer fiber layer. Yarn was spun consisting of: chopped glass in the core and wrapping positions; glass as the core wrapped with synthetic textile fibers; long staple β-silicon carbide whiskers wrapped with glass and synthetic fibers. The operating limits for spinning yarn with the apparatus were determined.

Fiber reinforced epoxy composites were formed using yarn spun with the vortex device. The mechanical properties were comparable to values obtained on extruded discontinuous fiber composites.

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## INTRODUCTION

For stiffness-limited applications, the most efficient utilization of high modulus, discontinuous reinforcements in a composite material is obtained when the fibers are aligned parallel to a principal axis (1). However, one of the major shortcomings in the field of advanced composite materials is the absence of methods to package short stiff fibers in collimated form for processing at a later time. In particular, utilization of minute single crystalline whiskers (2) demands their availability in a form which minimizes handling. Presently a sheet material is available (3) which contains aligned, discontinuous fibers in a partially cured thermoset resin. The high degree of alignment is maintained during the final shaping and curing of the sheet. However, there continues to be a requirement for a resin-free package, such as yarn of axially oriented fibers, suitable for filament winding and related composite fabrication procedures.

Processes to form a filament of aligned fibrils embedded within a carrier medium were developed concurrently by Parratt (4) and Schierding and Deex (5). However, in each case when the medium was removed, the filament had minimal handling strength and required immediate penetration with the matrix material. Attempts (6,7) to modify conventional textile processes to spin whisker yarns provided the impetus in this laboratory to use vortex spinning to form yarn. A method was developed (8), similar in principle

to that described by Strang (9) for textile yarns, to spin integral mixtures of high modulus fibers entrapped among textile (binder) fibers. The vortex spinning device is based on the principle that discontinuous fibers can be helically twisted into a yarn from the vortex created at the fixed tube-rotating junction of the spinning assembly. The main advantage of this type of formation is that no seeding is needed to start the yarn. In this process, as well as any other fluid vortex spinning process, a false twist is imparted to the yarn by an axial gradient or gradient in the angular velocity along the tube axis . This occurs because the initial rotation reference of the fiber is also the final rotation reference. Details of reverse or false twist are described in the Appendix.

The yarn spun with the original device did exhibit two major disadvantages with respect to its use as a reinforcing phase in composite materials. First, the high modulus fibers were mixed with low modulus fibers, e.g., synthetic textile fibers, which restricted the volume loading of the high modulus component. Second, while the yarn was essentially uniaxial, all the fibers were twisted, and thus, there was a large angle between the fibers and the principal yarn direction.

In this report the modified device and the spinning results obtained with this apparatus are described. The yarns consisted of an axially oriented core of high modulus short fibers wrapped with the same or lower modulus discontinuous fibers. Fiber reinforced composites were formed and tested using the spun yarn as the reinforcing phase.

EXPERIMENTAL

A complete description of the single slurry, fixed tube-rotating tube vortex spinner was reported previously (8). Using that device a two-component yarn was formed consisting of an integral mixture of high and low modulus twisted fibers. Here modifications to that apparatus are described for the spinning of a yarn with a core of aligned high strength, high modulus fibers helically wrapped with a thin outer layer of fibers. In the modified device the single slurry was replaced with separate slurries for the core fibers and the outer wrapping fibers. A sketch and photographs of the modified apparatus are shown in Figs. 1-3.

Stainless steel tanks with 1800 ml capacities were used to contain the slurries. The tanks were similar to the one used with the single slurry device. A stainless steel tube (d = 3/8") with a converging conical entrance extended into each tank from the top to within 1/2" of the bottom. The tube for each tank was an integral part of the lid which bolted onto the tank; an O-ring was used to provide a seal for pressurizing each tank. Each tube, equipped with ball values, led to a spinning head where the fibers were combined into their relative radial positions by a concentric tube arrangement.

The assembly was oriented vertically to eliminate gravitational effects on the spinning process. Flow was initiated by controlling the pressure in each slurry tank with nitrogen pressure (0-110) psi). The rotating tube speed was controlled over the range 600-3600 rpm by a motor-controller (Electrocraft, model E-600).

Spinning Heads

The positioning of the fibers from each slurry into the fixed tube of the spinning assembly was the most important design consideration for the modified device. The main criterion was that the fibers be arranged such that at the fixed tube-rotating tube junction, a composite yarn could be spun comprising a core section of axially aligned fibers and an annular section of wrapping fibers. The section of the spinning apparatus where the two slurries were combined is referred to as the spinning head.

Two spinning heads were designed to evaluate different methods of joining the tubes used to transport the fibers from the two slurry tanks. The flow at the region that the core and wrapping fiber slurries were combined within the spinning head was markedly affected by the design features. In both designs one of the transport tubes was fixed vertically throughout the entire assembly and aligned with the fixed tube-rotating tube junction; the other tube was introduced through the side of the spinning head.

The first spinning head (No. 1) is shown in Fig. 4. The core fibers flowed through the vertical tube to the spinning head and the wrapping fibers flowed into the annular region through the side tube. The second spinning head (No. 2), shown in Fig. 5, was designed so that the wrapping fiber slurry would flow in the vertical path, and the core fiber tube was introduced through the wall of the annular region. The core tube was curved to a vertical position and centered in line with the fixed tube-rotating tube junction.

Comparison of the two heads in operation indicated that the No. 2 head design was superior. The main limitation with No. 1 was that the wrapping fibers often caught on the center tube and plugged the area. For all of the experimental spinning results reported here, the No. 2 head was used.

In the No. 2 head the core tube was made of standard 1/4" stainless steel tubing and the annular casing was 5/8" stainless tubing with a 1/16" wall. The inlet to the spinning head was standard 3/8" stainless tubing. The original barrel was 1 1/8" long; it converged from an outer diameter (OD) of 5/8" to 0.403", and included a 1/4" inner diameter (ID) straight section 5/8" long.

In the initial experiments with the No. 2 head excellent quality 2-component yarn was formed with a well-wrapped axially aligned core of fibers. However, very close control of the spinning speed and the flow rates was required. When the ratio of core and wrapping fiber concentrations was varied, a yarn could be spun, but on occasion it extended back through

the barrel into the annular region, and caught on the center tube and converging wall. The yarn generally broke when this occurred. During the initial trial experiments with the No. 2 head and the original barrel, maximum lengths of 10 to 15 feet were formed prior to yarn breakage.

To eliminate the breakage problem, the No. 2 head was altered to extend the spinning zone away from the region the fibers were combined within the head.

The barrel was extended by joining the same basic converging section of the original barrel to a 2 1/2" tube. The effect of diameter was also investigated, using 5/32" and 13/64" tubes (barrels A and B, respectively); the modified barrels are also shown in Fig. 5. Tests using both barrels were successful and continuous spinning was readily obtained. Whereas the degree of wrapping of the outer fibers around the core fibers was not as great as that obtained with the short barrel, continuous spinning was possible with the longer barrels. In the original barrel, the outer fibers approached the core fibers from a non-axial position and were simultaneously twisted. From the point of view of wrapping this design consideration was superior.

Spinning Tube Assemblies

During the experimental investigation with various combinations of core and wrapping fibers, it was necessary to change the diameter of the spinning tubes in order to form continuous yarn. Two of the tubes employed were glass with inner diameters (ID) of 4mm and 6mm. In addition, a stainless steel tube was used with an ID of 13/64" (5mm). When these three tubes were combined with the various barrels for the No.2 head, there was a total of seven spinning assemblies (A to G). The spinning tube assemblies are described in Table 1.

Slurry Preparation

Totally dispersed fiber slurries were required for the spinning of yarn. In Table 2 the fibers used in this work are listed, with their corresponding average diameters; glass, graphite, and silicon carbide whiskers were the high modulus fibers and Acrilan and rayon were the low modulus synthetic fibers. The suspending fluid for all of the slurries was corn syrup (CS), with viscosities in the range 100 to 18,000 poise at 25°C. The fluids are described in Table 2 according to the manufacturer's code numbers and the viscosities. Intermediate viscosities could be obtained by boiling the low viscosity fluids, by mixing two types or by temperature variation.

The techniques for dispersing high and low modulus fibers, described previously in the report on the single slurry device, were applicable here. Glass fiber/corn syrup mixtures were

dispersed by rotating a Teflon cylinder (length = 5", diameter = 2") in a 2000 ml beaker containing the slurry. However, this method did not provide 100% dispersion if the viscosity was very high. Also, the Weissenberg effect (10) was encountered on several occasions with the slurries climbing the rotating shaft. The technique for dispersing lower modulus fibers was an extension — compression kneading type stroking action of the Teflon cylinder. It was also used for dispersing some of the high modulus fiber slurries. Fiber length for the glass and synthetic fibers was generally 1/2" or 3/4". A complete list of the slurries prepared in this investigation is presented in Table 3. The dispersion techniques are described as rotation and stroking for the former and latter techniques, respectively. A few silicon carbide whisker slurries were prepared from a limited quantity of the crystalline material. Details are presented in the Experimental Results section. A single graphite fiber slurry (CS-3) was prepared and the fiber length decreased from 3/4" to less than 1/8" during the dispersing step. As a result, experiments with graphite were not continued.

## EXPERIMENTAL RESULTS

### Yarn Formation

The conditions for spinning core and wrapping fibers into a yarn with the modified two-slurry device were determined from four yarn parameters used to assess the spinning. They were the degree of twist of the wrapping fibers, the yarn diameter and strength, the volume concentration of the two components, and the distribution of the component fibers in the yarn.

In Table 4 a complete summary of the spinning experiments is presented, and each is described by a "Spinning Number". The process variables specified in Table 4 include the rotating tube speed, the slurry flow rates (specified by pressure in the core [C] and wrapping [W] fiber slurry tanks), the take-up velocity, and in addition, the spinning assembly used. For each spinning experiment the wrapping-fiber and core-fiber slurry numbers are specified (details are listed in Table 3); also, the wrapping and core fibers are listed. For some of the experiments listed in Table 4, only the wrapping fiber slurry was used; in those cases a pressure value is indicated only for the wrapping fiber slurry (W).

The initial experiments with the modified device were carried out to test the wrapping fiber slurry portion of the apparatus. The spinning with this one tube was very similar to the spinning experiments reported earlier with the single slurry device (8). One-component and an integral mixture of two-component yarn was spun using the wrapping slurry tank. In the previous work Acrilan was used as the synthetic carrier fiber since it was generally unaffected by water or corn syrup in the temperature range of interest (25°C-60°C). Spinning experiments CS-1, CS-2 and CS-4, using Acrilan, Acrilan-glass, and Acrilan— β-Silicon Carbide Whisker fibers, respectively, duplicated results obtained earlier.

The ultimate purpose for spinning a yarn with core fibers and outer wrapping fibers was to utilize the aligned core of high-strength, high-stiffness fibers as the reinforcing phase for composite materials. To obtain maximum reinforcement, the yarn with synthetic wrapping fibers was to be charred, with the carrier fibers volatilized. Burn-off experiments with Acrilan-glass mixtures demonstrated that during volatilization there was severe curling and shrinkage of Acrilan. Thus, core fibers could not be maintained in a high degree of alignment when a burn-off of Acrilan was required.

Rayon was selected as an alternate carrier fiber since it does not shrink during volatilization at 600°C. Rayon has a very large water absorption coefficient, compared to Acrilan, which caused a viscosity increase in the corn syrup and a resulting change in fiber properties. Fortisan and triacetate rayon, as described in Table 2, were used; the performance of the triacetate as a wrapping fiber was superior to that of the Fortisan rayon.

The requirement of different spinning assemblies for the various fibers arose during attempts to spin one-component Fortisan rayon yarn (CS-5 thru CS-11, excluding CS-7). High quality Fortisan rayon was spun after determination of a suitable combination of components for the assembly. Triacetate rayon was successfully spun (CS-18) at higher fiber concentrations than Fortisan rayon because of the lower water absorption.

V. .y small diameter β E-glass fiber without a textile carrier ''ber was readily spun (CS-7, PY-15 and PY-23) into a one component twisted yarn from the wrapping slurry tank. In Fig. 6 a mat of glass is shown which had been spun (PY-23), rinsed with water to remove the corn syrup, and drawn onto a take-up drum. Later it was layered, cut and removed in mat form. Higher manigification of the same mat is shown in Fig. 7; the solid circle in the picture is a 1/4" dot.

Strands of spun yarn (PY-23 and PY-15) are shown in Fig. 8 to demonstrate the degree of twist possible with the wrapping fiber slurry tank. These results completed the preliminary evaluation of yarn formed using only the wrapping fiber slurry tank of the modified apparatus.

Operation of the entire two-slurry apparatus was demonstrated initially with yarn spun of chopped E glass fibers as the core and Acrilan wrapping fibers (CS-13). The use of Acrilan as a wrapping fiber was limited to initial trial experiments with the two-slurry tanks since yarn with an Acrilan component did not qualify for use in composites. The first continuous spinning of glass and triacetate rayon was readily achieved (CS-16) on the basis of the experience obtained from spinning with a single slurry tank. For the CS-16 yarn, the volume fraction of glass fiber was 0.11 (the volume fraction of core fiber conta ned in most two-component yarn was determined and the values are listed in Table 5). In Fig. 9 the appearance of glass and triacetate rayon wound on drums is shown for yarns PY-1 and PY-27. Also shown in Fig. 9 are three one-component yarns spun from the wrapping slurry fiber tank and wound on drums: Fortisan rayon, Acrilan and glass, as denoted by the spinning numbers CS-9, CS-12 and PY-15, respectively.

In the experiments carried out with glass as the core fiber and triacetate rayon as the wrapping fiber (CS-14, CS-16, CS-17, CS-21, PY-1 to PY-14, PY 24 to PY-27), spinning assemblies D, E and G (see Table 1 for details) were used. Continuous yarn could be spun provided a critical concentration for each slurry was not exceeded. These concentrations were: [18g glass/1400 ml of 1027 corn syrup], and [18g rayon/1400 ml of 1621 corn syrup]. The viscosities ($\eta$) of the fluids in the two slurry tanks was varied in the series of glass-triacetate rayon experiments, and the results indicated that the most reliable spinning was obtained when $\eta$ (core) > $\eta$ (wrapping) by one to two orders of magnitude. Also, the pressure, which controlled the flow of fibers from each tank, was systematically varied and an aligned core was obtained only when the flow of fibers in the annular region exceeded the flow through the center tube.

The yarn represented by PY-26 was spun of glass and triacetate rayon with all the process variables optimized on the basis of previous spinning experiments. The fiber slurry (GS-11) was a combination of S-glass and the red E-glass at the critical concentration for the 1027 fluid. The triacetate rayon slurry (CS-27) was also at the critical concentration for the 1631 fluid. This particular yarn contained the highest volume fraction of core fibers achieved with the two slurry apparatus. The process conditions for this particular yarn were: rotating tube speed, 860 rpm; yarn take-up velocity, 0.45 in/sec; and slurry tank

pressures, C = 75 psi, W = 50 psi. Photographs of the PY-26 yarn are shown in Fig. 10. In yarn PY-12 the red E-glass and triacetate rayon were combined in nearly the same combination as the glass-triacetate rayon yarn PY-26. However, the process conditions used were different, and yarn PY-12 had substantially different twist characteristics and a glass volume fraction of only 0.06. Two photographs of yarn PY-12 are shown in Fig. 11.

The synthetic component of a glass and triacetate rayon fiber yarn was removed by a burn-off at 600°C. The volatilization did not disturb the core fiber alignment. In Fig. 12 photographs are shown of strands from two glass yarns (PY-1 and PY-9) after burn-off of the triacetate rayon component.

Although the apparatus was designed to spin a yarn with high modulus core fibers and lower modulus wrapping fibers, yarn was successfully spun (PY-16 to PY-21) with chopped E-glass fibers as the core and smaller diameter β E-glass as the wrapping fibers. The experiments were initiated for two reasons: first, β E-glass was easily spun into yarn using the wrapping slurry tank as described above, and second, the degree of wrapping fiber twist could be controlled at a minimum level. Glass-glass combinations were spun with negligible twist in the wrapping fibers (PY-20); a portion of the PY-20 yarn in mat form is shown in Fig. 13.

The core consisted of red E-glass fibers which appear as faint horizontal streaks in combination with the unstained outer glass fibers. Two examples of glass-glass yarn with a high degree of wrapping fiber twist are shown in Fig. 14, corresponding to yarn PY-17 and PY-21. These 100% glass yarns were suitable for direct impregnation with a thermosetting resin, followed by curing to a rigid reinforced polymer composite.

The glass experiments were followed by an attempt to form a yarn of long staple β-silicon carbide whiskers without wrapping fibers. A slurry containing 6.5 gm of silicon carbide whiskers was used, and a yarn was spun which demonstrated that the few long whiskers ($\ell$ > 0.25 in) would twist into a yarn. However, the strand was too weak to evaluate. Observation under a microscope showed that there was an aligned core with an outer "fuzz" of small whisker filaments. However, yarns were formed with the silicon carbide whiskers in the core and triacetate rayon as wrapping fibers (CS-19 and CS-20). A single experiment with partial success was carried out with silicon carbide whiskers as the core, wrapped with β E- glass. The experiments with silicon carbide whiskers were limited because of a minimum supply of whiskers with aspect ratios greater than 25.

## Formation of Fiber/Polymer Composites

Fiber reinforced composites were formed by cutting a mat of yarn to 4" x 8", impregnating with epoxy (Shell's Epon 828 and curing agent "Z"), and curing under pressure in a positive pressure mold. Test specimens were cut from the sheets and mechanical properties determined with an Instron tester. An example of the composite formation process is described as follows: Yarn (PY-19) with glass core fibers and glass wrapping fibers which had been wound on a drum, were cut and removed as a mat; removal of the corn syrup was completed by careful washing and heating; the fibers and resin were combined by vacuum impregnation with resin. Average properties are listed in Table 6. Yarn with a glass core and triacetate wrapping fibers was also used in the formation of composites. The composites were made with and without the triacetate rayon removed. The mechanical property data for these composites are also lsited in Table 6.

One of the most important variables affecting the mechanical properties of discontinuous fiber reinforced composites is the orientation distribution of the fibers (11). The distribution in the composite formed with the PY-19 yarn was determined using a techni[illegible] described in detail by Goettler (12). The resulting orientation distribution is given in Table 7.

## DISCUSSION

The results presented in Table 4 demonstrated that the two-slurry vortex apparatus provided a method of spinning yarn with an aligned core of discontinuous high modulus fibers wrapped with synthetic fibers such as triacetate rayon, or small diameter glass fibers. The yarn can be readily reduced to a mat of aligned core fibers by volatilizing the synthetic fibers. However, ne formation of yarn was very dependent on the conditions for the process and material variables, particularly the relative flow rate of the slurries and the relative viscosity of the suspending fluids in the two tanks. A requirement that the flow rate of the fibers in the annular region exceed the flow rate of the core fibers was deduced after "puffs" of core fibers in yarn appeared regularly when the flow rate of the two suspensions was about equal. An example of "puffs" is shown in Fig. 15 for a yarn of glass fiber and triacetate rayon fiber (PY-14). During the spinning of that yarn the ratio of wrapping fiber flow rate (pressure) to core fiber flow rate was varied between 1.0 and 2.0; the "puffs" occurred whenever the ratio approached 1.0. The variation of fluid viscosity in the two tanks indicated that a much higher viscosity was preferred for the core fiber slurry relative to the wrapping fiber slurry. The principal evidence was an observation that the core fibers were held as a unit during spinning when the viscosity ratio was between $10^1$ and $10^2$. The high viscosity

core slurry could not twist at the fixed tube-rotating tube junction; however, the motion of the wrapping fibers was not restricted, and they twisted helically due to the axial vorticity gradient.

As indicated in the experimental section, the final design of the spinning head was a compromise in order to continuously spin two-component yarn. During the final design adjustments the following was observed: first, the twist of the wrapping fibers was more easily controlled when the annular slurry approached the core slurry (center axis) concentrically in a non-axial direction; second, whenever the two slurries emerged from the spinning head in a non-concentric pattern, the intended core fibers formed a helix on the annular slurry; third, the required flow rates were a function of the spinning head barrel length, and in turn, the ratio of flow rates determined the concentration of the two components.

The mechanical property values listed in Table 6 are slightly higher than properties in the literature (13) for comparable aligned short glass fiber/epoxy composites formed by extrusion. However, the orientation distribution of the reinforcing phase was broad for the composites prepared with yarn, and thus, lower levels of mechanical properties would be anticipated. Although the formation of the yarn provided a very uniform overlapping of the single dispersed fibers, the number of experiments was not sufficient to evaluate the effect of fiber distribution in the yarn with mechanical properties.

## CONCLUSIONS

A two-slurry vortex spinning device was designed and demonstrated with the formation of a two component yarn. Hydrodynamic forces, produced by an axial vorticity gradient in the spinning tube, twisted discontinuous fibers into a yarn with an axial core of high modulus fibers (glass and whiskers) and peripheral fibers of the same or lower modulus (glass or synthetic textile fibers). To form the yarn, two slurries of nominally the same concentration (0.5 to 1.0%) were used. Spinning problems and core-fiber damage were minimized when the viscosity of the core-fiber slurry was maintained one to two orders of magnitude higher than the annular slurry. The slurries were introduced into the spinning zone through a spinning head which positioned the fibers. The design of the spinning head required that the annular flow exceed the core flow, and it provided adequate wrapping of the core fibers by the peripheral fibers.

The maximum volume fraction of glass in a two-component yarn of glass with synthetic fibers was 0.36. However, 100% glass yarn was spun when both the core fiber slurry and wrapping fiber slurry contained glass. Triacetate rayon fibers were easily removed from a two-component yarn and the remaining core fibers exhibited a very high degree of alignment. A limited supply of long staple β-silicon carbide whiskers was used to demonstrate that very high modulus, small diameter fibrils can be spun into a yarn.

Composites were molded with a thermosetting matrix using the following yarn compositions as the reinforcing phase: glass as the core combined with glass wrapping fibers; glass in the aligned core position (with the triacetate rayon removed); glass in the core position combined with triacetate rayon wrapping fibers. The mechanical properties of the composites were comparable to values obtained with extruded short glass fiber composites.

## Acknowledgments

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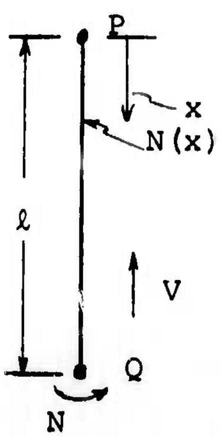
## APPENDIX

### Reverse or False Twist

In a vortex tube spinning apparatus, twist is imparted by means of an axial vorticity gradient or gradient of the angular velocity along the tube axis. Therefore, a false twist must be present in the spinning process. This is true since the initial rotation reference of the fibers is also the final rotation reference unless elaborate equipment is utilized to change the rotation of one of these reference rotations, e.g., a take-up system that rotates at the tube speed.

The reverse twist produced by a vortex spinning assembly can be analyzed as follows: Consider a straight line passing through points P and Q with a velocity V. The line has zero rotation at P and a rotation rate N at Q.




Determination is now made of the rotation rate of a non-fixed point at x on the line which is rotating at N(x) and advancing at the velocity V with the conditions that the rotation at one end is zero and at the other is a constant.

$$N(x) = N(x/\ell)$$

The total twist imparted to the line in going from Q to P is determined by first establishing the change in the number of revolutions, R, with respect to x:

$$dR = N\, x/\ell \; dt = N\, x/\ell \; \frac{dx}{dx/dt}$$

but

$$V = -\frac{dx}{dt}$$

Therefore,

$$dR = -\frac{Nx}{\ell V}\, dx$$

Integration between Q and P gives the total number of revolutions imparted to the line or the total twist in going from Q to P.

$$R = \int_{\ell}^{0} \frac{Nx}{\ell V}\, dx$$

or

$$R = \text{twist} = \frac{-N\ell}{2V}$$

Thus, the reversed twist is directly proportional to the reversing rotation N and the distance to the non-rotating state $\ell$, and inversely proportional to the velocity of the moving line or yarn.

The creation of twist initially to produce a yarn may be visualized by inverting the sketch. For such a case, the yarn goes from a stationary rotation reference to a rotating reference.

TABLE 1: Spinning Tube Assemblies

| TITLE | | DESCRIPTION |
|---|---|---|
| A | 4 mm ID | straight through glass spinning tube |
| B | 6 mm ID | straight through glass spinning tube |
| C | 6 mm ID | glass tube with short barrel of No. 2 spinning head |
| D | 13/64" (5mm) ID | stainless steel spinning tube with short barrel of No. 2 spinning head |
| E | 13/64" ID | stainless steel spinning tube with 2" section soldered to short barrel of No. 2 spinning head. |
| F | 13/64" ID | stainless steel spinning tube with barrel "A" of No. 2 spinning head. |
| G | 13/64" ID | stainless steel spinning tube with barrel "B of No. 2 spinning head. |

*Spinning tube length = 6".

## TABLE 2: Fibers

| Fiber | Average Diameter mm | Average Diameter mils ($10^{-3}$ in) |
|---|---|---|
| Beta (β) E-glass (Owens Corning Fiberglass Corp.) | 0.004 | 0.16 |
| S-glass (Ferro Corp.) | 0.010 | 0.41 |
| E-glass [Red] (Gustin Bacon) | 0.013 | 0.50 |
| E-glass (Johns Manville, CS 308A) | 0.013 | 0.51 |
| Graphite (Union Carbide, WYF 130-1/2, Thornel 50) | .007 | 0.24 |
| β-Silicon Carbide Whiskers (General Technologies Corporation, 5A) | .001 | 0.06 |
| Fortisan Rayon (Celanese) | 0.009 | 0.36 |
| Triacetate Rayon (Celanese) | 0.024 | 0.94 |
| Acrilan 57A (Monsanto) | 0.018-.019 | 0.70-0.75 |

### Corn Products Corn Syrup Fluids

| Code Number | Viscosity |
|---|---|
| 1621 | 100 - 150 poise |
| 1631 | 350 |
| 1027 | 18,000 |

TABLE 3

SPINNING SLURRIES

| Slurry No. | Fiber | Suspending Fluid: Corn Syrup (C.S.) | Concentration (g fiber/ml fluid) | Dispersion | Comments |
|---|---|---|---|---|---|
| CS-1 | 3/4" Acrilan 57A | 1621 | 8.2/1400 ml | stroking of rod in C.S. heated to 60°C | ——— |
| CS-2 | 1/2" Johns-Manville CS-308A Glass 3/4" Acrilan 57A | 1621 | (8g glass + 5g 57A)/1400ml | stroking at 60°C | glass fired at 600°C |
| CS-3 | 3/4" Union Carbide Graphite | 1621 | 6g/1400ml | rotating cylinder at 300-400 RPM | fiber damaged. 3/4" to 1/8" |
| CS-4 | SiC Whiskers (variable length) (5A) 3/4" Acrilan 57A | 1621 | (0.7g SiC + 7g 57A)/1000ml | rotating gl. stroking of rod CS heated to 60°C | 80 ft. spun |
| CS-5 | 3/4" Fortisan Rayon | 1621 | 4g/(1400-400)ml | rod/rotation/gl. stroking | separated fluid removed. stroking method developed here. |
| CS-5A | 3/4" Fortisan Rayon | 1621 | 8.09/1000ml | stroking/ rotation | knots formed removed 2-3g |
| CS-6 | 1/2" Fortisan Rayon | 1621 | 7.29/1200ml | stroking | viscosity appeared much higher than CS-4 |
| CS-7 | 3/4" Glass (β E glass) | 1621 | 15g/1200ml | stroking at 60°C | 200 ml C.S. added to original 1000 ml slurry |
| CS-8 | 3/4" Fortisan Rayon | 1621 | 7g/1000ml | " | fiber soaked 4 days in $H_2O$; diluted 100ml |

TABLE 3 (Continued)

| Slurry No. | Fiber | Fluid | Concentration (g fiber/ml fluid) | Dispersion | Comments |
|---|---|---|---|---|---|
| CS-9 | 3/4" Fortisan Rayon | 1621 | 7g/1400 ml - 2g | stroking/rotation | lumps formed |
| CS-10 | 3/4" Fortisan Rayon | 1621 | 7g/1400 ml | " | straining |
| CS-11 | 3/4" Fortisan Rayon | 1621 | 9g/1400 ml | " | plugged |
| CS-12 | 3/4" Acrilan 57A | 1621 | 10g/1400 ml | " | |
| CS-13 | 3/4" Acrilan 57A | 1621 | 12g/1400 ml | " | |
| CS-14 | 3/4" Triacetate Rayon | 1621 | 9g/1400 ml | " | |
| High Modulus (HM) Slurry #1 | 1/2" Johns Manville CS-308A Glass | 1621 | 17.5g/1200 ml | rotation | |
| CS-15 | 3/4" Triacetate Rayon | Strained 1621 | 8-9g/1400 ml | stroking | |
| CS-16 | 3/4" Triacetate Rayon | 1621 | 12g/1400 ml | " | 1621-3 some precipitation noticed crystallized |
| High Modulus Slurry #2 | 1/2" Johns-Manville CS-308A Glass | 1621 | 40g/1400 ml | rotation | |
| CS-17 | 3/4" Triacetate Rayon | 1621-3 | 18g/1400 ml | | |
| CS-18 | 3/4" Triacetate Rayon | 1631 | 15g/1400 ml | " | run at various pressures |

TABLE 3 (Continued)

| Slurry No. | Fiber | Suspending Fluid | Concentration (g fiber/ml fluid) | Dispersion | Comments |
|---|---|---|---|---|---|
| CS-19 | 3/4" Triacetate Rayon | 1631 | 25g/1400 ml | stroking | |
| SiC Whiskers | 5A SiC Whiskers | 1621-3 | 6.5g/900 ml | rotation | fibers separated upward and turned thick |
| CS-20 | 3/4" Beta E-Glass | 1631 | 21g/1400 ml | stroking | |
| CS-21 | 3/4" Triacetate Rayon | 1621-3 | 18g/1400 ml | " | |
| CS-22 | 3/4" Triacetate Rayon | 1621-3 | 18g/1400 ml | " | better dispersion than |
| CS-23 | 3/4" Triacetate Rayon | 1621-3 | 16g/1400 ml | " | |
| CS-24 | 3/4" Triacetate Rayon | 1621-3 | 18g/1400 ml | stroking | |
| CS-25 | 3/4" Triacetate Rayon | 1027 | 18g/1400 ml | " | C.S. heated to 45°C |
| CS-26 | 3/4" Triacetate Rayon | 1631+1027 | 19.3g/(1000 ml 1631 + 500 ml 1027) | " | C.S. heated to 35-40° |
| CS-27 | 3/4" Triacetate Rayon | 1631 | 18g/1400 ml | " | |
| CS-28 | 3/4" Triacetate Rayon | 1621-3 | 18g/1400 ml | " | crystallized; non-flowable |
| CS-29 | 3/4" Triacetate Rayon | 1621-3 | 15.5 g/1460 ml | " | |
| CS-30 | 3/4" Triacetate Rayon | 1621-3 (boiled to 1100 poise) | 21g/1400 ml | " | |
| CS-31 | 3/4" Triacetate Rayon | 1621-3 (heated) | 18g/1400 ml | " | |

TABLE 3 (Continued)

| Slurry No. | Fiber | Fluid | Concentration (g fiber/ml fluid) | Dispersion | Comments |
|---|---|---|---|---|---|
| GS-1 | 3/4" Beta E-Glass | 1027 | 20g/1400 ml | rotation | rotation method yields tufts or tails of fibers unsatisfactory |
| GS-2 | 3/4" S-Glass | 1027 | 9g/700 ml | rotation | |
| GS-3 | 3/4" S-glass | 1027 | 15g/700 ml | rotation | plugged -- probably due to tail |
| GS-4 | 3/4" S-Glass | 1027 | 9g/700 ml | rotation | 18g/1400 ml unsuccessful in dispersion tail formed |
| GS-5 | 3/4" S-Glass | 1631 | 16.2g/1280 ml | rotation | tailing minimized |
| GS-6 | 3/4" Red E Glass | 1027 | 9.22g/700 ml | stroking | rotation unsuccessful |
| GS-7 | 3/4" Red E Glass | 1631 | 19.44/1400 ml | " | |
| GS-8 | 3/4" Beta E Glass | 1621-3 | 17g/1400 ml | " | glass yarn produced |
| GS-8a | 3/4" Beta E Glass " | 1621-3 | 18g/1400 ml | " | C.S. heated to eliminate crystals in PY-23 |
| GS-9 | 3/4" Red Glass | 1027 | 18.45g/1400 ml | " | |
| GS-10 | 3/4" Beta E Glass | 1621-3 | 16.1g/1350 ml | " | plugged pot nozzle |
| GS-11 | 3/4" S Glass + 3/4" Red E Glass | 1027 | (16g S-Glass + 4g Red Glass/ 1400 ml | " | |

TABLE 4

| Spinning No. | Slurry No.* | Fiber | Tube** Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure*** (PSI) C | Pressure*** (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| CS-1 | CS-1 | Acrilan 57A | A | 2000-2200 | 0.3-0.4 | -- | 10,17 | 20-25 feet of yarn produced. first basic production. |
| CS-2 | CS-2 | Acrilan 57A<br>Johns-Manville glass | A | 2000 | 0.66 | -- | 20 | seven feet of yarn produced. glass distributed at all radii. |
| CS-3 | CS-3 | Acrilan 57A<br>Graphite | A | ---- | ---- | -- | -- | fibers reduced from 3/4" to 1/16" during dispersing. no spinning performed. |
| CS-4 | CS-4 | Acrilan 57A<br>SiC Whiskers | A | 1800 | 0.66 | -- | 17 | eighty feet of yarn produced-no breaks occurred and alignment of small whiskers poor and large whiskers axial. yarn very fine. |
| CS-5 | CS-5 | Fortisan Rayon | A | 1200-1300 | 0.18 | -- | 20-25 | spinning proceeded for ten minutes. concentration of fibers increased. flow reduced to total plugging. |
| CS-6 | CS-6 | Fortisan Rayon | A | 800 | ---- | -- | 35-40 | concentration of flowing slurry not constant. spinning tube diameter too small and caused straining. temperature elevation at 30° and 55° helped flow but straining still occurred to point of plugging. |
| CS-7 | CS-7 | Beta E-glass | A | 750 | 0.008 | -- | 35 | slurry thick. full drum of yarn produced with few breaks straining occurred toward end of run. |

* For two-component yarn spun from the wrapping and core fiber slurries, the wrapping slurry No. is indicated above the core slurry No.

** Spinning tube assemblies are identified in Table 1.

*** The core and wrapping fiber slurries are indicated by C and W, respectively

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure C | (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| CS-8 | CS-8 | Fortisan Rayon | A | ---- | ---- | -- | -- | spinning unsuccessful--slurry too viscous for small tube. dilution of slurry with 100 ml $H_2O$ not helpful. |
| CS-9 | CS-9 | Fortisan Rayon | A | 750 | 0.78 | -- | 17 | new take-up unit. twenty feet of yarn spun with 10-20 additional feet spun with several breaks occurring. slurry concentration too low for continuous spinning. |
| CS-10 | CS-10 | Fortisan Rayon | A | 800-900 | 0.78 | -- | 17 | fiber count decreased during spinning due to plugging or straining causing discontinu-[illegible] operation. |
| CS-11 | CS-11 | Fortisan Rayon | A | 800-900 | 0.78 | -- | 17-40 | operation to total plugging. |
| CS-12 | CS-12 | Acrilan | C | no | record | -- | -- | yarn irregular in diameter but strong. |
| CS-13 | CS-13<br>Glass Slurry | Acrilan<br>E Glass | C | 1500-2700<br>3600 | ---- | 25<br>25 | 18<br>40 | yarn produced. first run of high twist and second of low twist due to increased flow. first basic production of composite yarn. |
| CS-8 (rerun) | CS-8 | Fortisan Rayon | D | 1800-1950 | 2.55 | -- | 60 | spinning was continuous but the yarn was not as uniform as was spun with a straight through 3 mm ID glass tube. the ID of the barrel was a little larger than that of the 5/16" OD SS spinning tube. this fact may account for the poorer yarn quality. |

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure C | (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| CS-9 (rerun) | CS-9 | Fortisan Rayon | B | 1650 | ---- | -- | 20 | Electrocraft motor controlle used for tube speed. most successful spinning to date. no breaks, straining, etc. continuous spinning of complete batch. larger tube provides better spinning. |
| CS-10 (rerun) | CS-10 | Fortisan Rayon | B | 1650 | ---- | -- | 25<br>30<br>35 | spinning was continuous with only a few breaks caused by air bubbles. variable diameter yarns formed by changin flow rate and holding take-up constant. |
| CS-11 (rerun) | CS-11 | Fortisan Rayon | B | 1650 | ---- | -- | 30 max | plugging occurred probably due to poor dispersion. |
| CS-14 | CS-14<br>HM Slurry #1 | Triacetate Rayon E Glass | E | 2100<br>2150<br>2150<br>2150 | 0.93<br>2.15<br>2.15<br>2.15 | --<br>10<br>15<br>25 | 40<br>50<br>50<br>50 | slurry at 16°C; high modulus fibers introduc into LM stream. take-up speed increased and no twist was present in the yarn; a jump in RPM to 3500 didn't help. |
| CS-15 | CS-15 Glass Slurry with CS-14 run | Triacetate Rayon E-Glass | F | spinning unsuccessful-- problems | | | | |
| CS-15 | " | " | G | slurry plugged--dispersion not complete | | | | |

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure (PSI) C | W | Results |
|---|---|---|---|---|---|---|---|---|
| CS-16 | CS-16 HM slurry #1 | Triacetate Rayon E-glass | G | 3100 | 3.75 | 30 | 40 | continuous spinning of a composite yarn achieved. yarn contained 10.6 volume percent of glass. |
| CS-17 | CS-17 + HM slurry #2 | Triacetate Rayon E-Glass | G | 2500-2700 | 2.28 | 30 | 40 | initial spinning of low modulus fiber successful at 20 PSIG. composite yarn fair to poor. condition changing with time. |
| CS-18 | CS-18 | Triacetate Rayon | G | 1500-3000<br>1950<br>2100<br>2000 | 1.06<br>1.06<br>1.01<br>1.2 | --<br>--<br>--<br>-- | 25<br>35<br>45<br>55 | varied flow while holding take-up relatively constant. yarn diameter increased. no high modulus fibers were used. denier varied from 1000-1200 g/9000 meters. |
| CS-19 | CS-19 whisker slurry | Triacetate Rayon SiC Whiskers | G | 2300<br>2300<br>2300<br>1800-1960 | 2.3<br>2.3<br>2.3<br>2.3 | 25<br>20<br>29<br>50 | 30<br>40<br>36<br>65 | whiskers due to short lengths ( 1/4") were on outside of yarn as a fuzz. long whiskers were as core aligned axially. it appears that whisker slurry has too low a viscosity. whiskers appeared at pressure setting for third run. |
| CS-20 | CS-20 whisker slurry | Triacetate Rayon SiC Whiskers | G | 1050 | 0.63 | 31 | 41 | fifty feet of yarn spun before breakage occurred. molding made but corn syrup was not all washed off. spinning of whiskers alone produced aligned fibers too weak to handle as yarn. |

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure C | (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| CS-21 GS-1 | ---- | Triacetate Rayon Beta E-Glass | G | 600-700 | 1.8 | 81 | 22 | core present in yarn--twist negligible. at 1500 RPM core twists with outer fibers makes nice yarn. |
| CS-21 GS-2 | ---- | Triacetate Rayon S-Glass | G | 600-1500<br>2900<br>1500-1800<br>1500-1600<br>1800-2200<br>1000-1100 | --- | 80<br>80<br>75<br>75<br>75<br>49 | 20<br>38<br>31<br>31<br>31<br>22 | the last run in this series produced sufficient twist and uniformity but yarn appearance was very poor. relative pressure ratio of HM to LM should not be so high that the velocity of the HM fibers is greater than the LM fibers. |
| PY-1 | CS-21 GS-2 | Triacetate Rayon S-Glass | D | 1100 | 1.1 | 54 | 35 | the slower HM flow and higher low modulus slurry flow provided the right combination for spinning a continuous yarn a well twisted composite yarn was spun with 12.6 volume percent glass. |
| PY-2 | CS-23 GS-4 | Triacetate Rayon S-Glass | G | 1300<br>2100<br>1050<br>--- | 1.07<br>1.5<br>0.5<br>--- | 54-60<br>40<br>40<br>40-80 | 35 }<br>60<br>27-35 }<br>35-53 | fibers not twisted due to high flow rate.<br>yarn backed into spinning head in previous run and caused plugging. |
| PY-3 | CS-24 GS-4 | Triacetate Rayon S-Glass | G | 900 | 1.56 | 54 | 35 | viscous core held fibers together during spinning but RPM too low to impart twist. mat of well aligned untwisted fibers produced. |

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure C | (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| PY-5 | CS-24 GS-4 | Triacetate Rayon S-Glass | G | 1500-1600 | 1.56 | 54 | 35 | variable twist present due to surging flow. improvement over PY-3. |
| PY-6 | CS-24 GS-5 | Triacetate Rayon S-Glass | G | 2250 | 1.4 | 40 | 30 | spinning was continuous. proper conditions are closer to optimum. run stopped due to O-ring drive slipping. |
| PY-7 | CS-25 GS-5 | Triacetate Rayon S-Glass | G | 1000 | 0.77 | 40 | 36 | annular viscosity was greater than center viscosity. spinning produced well aligned core yarn wrapped with the triacetate fibers. control difficult and non-reproducible. full drum produced. |
| PY-8 | CS-25 GS-5 | Triacetate Rayon S-Glass | G | 780 | 0.85 | 66 | 84 | very successful spinning and controlled well. low modulus flow high enough to help align HM fibers. |
| PY-9 | CS-25 GS-5 | Triacetate Rayon S-Glass | G | 1000 | 0.85 | 66 | 84 | some excessive twisting of core fibers but burn off shows core of consistently aligned fibers. |
| PY-10 | CS-26 GS-6 | Triacetate Rayon Red E-Glass | G | 1500-2100 | 0.85 | 66 | 55 | settings varied. core helical in high twist areas of secondary twist. slurry not homogeneous. |

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure C | (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| PY-11 | CS-27<br>GS-6 | Triacetate Rayon<br>Red E-Glass | G | 750<br>1900-2000 | 0.85<br>1.3 | 55-60<br>80-85 | 40<br>75 | first run unsuccessful. second run produced yarn containing puffs of glass or balls of glass causing poor uniformity. HM slurry flow too high. |
| PY-12 | CS-28<br>GS-6 | Triacetate Rayon<br>Red E-Glass | G | 1800 | 2.65 | 101 | 66 | a complete drum was filled and overlapped with fibers of low twist and a few puffs of glass. the over-all yarn appearance was uniform. syrup of CS-28 crystallized. |
| PY-13 | CS-28<br>GS-7 | Triacetate Rayon<br>Red E-Glass | G | 2200-3000 | 2.65 | 60-90 | 60 | a uniform yarn with little twist was produced. the sample looked good enough to make into a composite. |
| PY-14 | CS-28<br>GS-7 | Triacetate Rayon<br>Red E-Glass | G | 2000 | 1.75 | 50-90 | 40-45 | CS-28 slurry crystallized. lumps form in spinning causing plugging. |
| PY-15 | GS-8 | Beta E-Glass | G | 2700-3000 | 1.5 | --- | 52 | pure glass spun very well through low modulus tubes. 80 feet of glass yarn produced. |
| PY-16 | GS-8<br>GS-7 | Beta E-Glass<br>Red E-Glass | G | 1050 | 0.85 | 54 | 45 | irregular yarn with red fibers in core and on outer periphery. LM flow too slow. |

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure C | (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| PY-17 | GS-8<br>GS-7 | Beta E-Glass<br>Red E-Glass | G | 1400 | 1.25 | 55 | 64 | yarn uniform produced of white outer fibers and red core fibers. puffs of red glass appeared and concentration of core fibers low in places. |
| PY-18 | GS-8<br>GS-9 | Beta E-Glass<br>Red E-Glass | G | 1400 | 1.25 | 71 | 64 | core slurry viscosity one order of magnitude higher than annular. yarn of definite core produced. relative spinning conditions close to optimum. |
| PY-19 | GS-8<br>GS-9 | Beta E-Glass<br>Red E-Glass | G | 1400<br>2200 | 2.17<br>2.17 | 70-80<br>70-80 | 80<br>80 | two overlapping layers were spun over 2/3 of the drum length. red core fibers uniformly distributed and the yarn appearance was uniform. mat was formed and molded into a composite of 37.5 volume percent glass. |
| PY-20 | GS-10 | Beta E-Glass<br>Red E-Glass | G | 2850 | 4.2 | 95 | 110 | two mats of yarn were formed, one of twisted glass fibers with a core of red glass. the other mat contains untwisted fibers due to slippage of the O-ring drive. suitable product for aligning whiskers. |

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velocity (in/sec) | Pressure C | (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| PY-21 | GS-10<br>GS-9 | Beta E-Glass<br>Red E-Glass | G | 1700 | 1.0 | 69 | 89 | spinning was continuous and produced a nicely twisted yarn with no breaks. red fibers were distributed unevenly throughout the yarn. no puffs occurred. a triple layer of yarn of width 3" was spun (6 grams). uniform twist and consistency existed. |
| PY-22 | GS-8a | Beta E-Glass | G | 1200-2000 | 2.95 | -- | 85 | yarn twist varied from no twist to ample twist. O-ring pulley not performing. |
| PY-23 | GS-8 | Beta E-Glass | G chain drive | 1300-1400 | 1.1-1.8 | -- | 65-90 | chain drive installed. speed ratio changed from 1.5 to 1.33. spinning was excellent. four mats of 61 grams of glass yarn were spun. the twist was uniform as was the appearance. |
| PY-24 | CS-31<br>GS-7 | Triacetate Rayon<br>Red E-Glass | G | 1300-1600<br>730 | 1.95<br>1.75 | 85<br>95 | 51<br>46 | no twist in yarn. the viscosity of the 1621 corn syrup appears to be too low. |
| PY-25 | CS-27<br>GS-7 | Triacetate Rayon<br>Red E-Glass | G | 860 | 1.1 | 75 | 6[illegible]-70 | both slurry viscosities same (1631). this combination does not protect core fibers. need high core viscosity. |

TABLE 4 (continued)

| Spinning No. | Slurry No. | Fiber | Tube Assembly | Spinning Speed (RPM) | Take-Up Velccity (in/sec) | Pressure C | (PSI) W | Results |
|---|---|---|---|---|---|---|---|---|
| PY-26 | CS-27<br>GS-11 | Triacetate Rayon<br>S-Glass + Red E-Glass | G | 860 | 0.45 | 75 | 50 | spinning very successful. yarn contained 35.9 volume percent glass. mat spun for molding. |
| PY-27 | CS-27<br>GS-11 | Triacetate Rayon<br>S-Glass + Red E-Glass | G | 930 | 1.1 | 75 | 52 | uniform yarn spun as in Py-26. volume percent of glass lower (15%). yarn uniform. |

TABLE 5

VOLUME CONCENTRATION OF GLASS IN YARN

| Yarn | Volume Fraction Glass |
|---|---|
| CS-16 | 0.11 |
| CS-21 + GS-2 I | 0.23 |
| CS-21 + GS-2 #1 | 0.30 |
| CS-21 + GS-2 #2 | 0.23 |
| CS-21 + GS-2 #3 | 0.21 |
| PY-1 | 0.13 |
| PY-2 | 0.09 |
| PY-3 | 0.06 |
| PY-4 | 0.08 |
| PY-5 | 0.08 |
| PY-6 | 0.12 |
| PY-7 | 0.15 |
| PY-8 | 0.03 |
| PY-9 | 0.15 |
| PY-10 | 0.18 |
| PY-11 | 0.10 |
| PY-12 | 0.06 |
| PY-13 | 0.09 |
| PY-14 | 0.12 |
| PY-24 | 0.08 |
| PY-25 | 0.11 |
| PY-26 | 0.36 |
| PY-27 | 0.15 |

TABLE 6. Mechanical Properties of Molded Composites

| Yarn | Volume Fraction Fiber in Composite | Modulus ($10^6$ psi) Tensile | Modulus ($10^6$ psi) Flexural | Strength ($10^3$ psi) Tensile | Strength ($10^3$ psi) Flexural |
|---|---|---|---|---|---|
| PY-19 | 0.38 | | 3.0 | | 64.5 |
| PY-26 (with textile yarn) | 0.30 | | 3.1 | | 42.7 |
| E glass (rayon removed) | 0.19 | 1.6 | | 27.1 | |
| E glass (rayon removed) | 0.22 | 1.8 | | 29.1 | |

TABLE 7

ORIENTATION OF GLASS FIBERS IN MOLDED COMPOSITE

YARN: PY19

FIBER: Glass

MATRIX: Epoxy

| Angle (Degrees off Axis) | % Orientation* |
|---|---|
| 0-5 | 12.5 |
| 6-10 | 10 |
| 11-15 | 12 |
| 16-20 | 11.6 |
| 21-25 | 10 |
| 26-30 | 9 |
| 31-35 | 7.7 |
| 36-40 | 3.3 |
| 41-45 | 4.2 |
| 46-50 | 2.4 |
| 51-55 | 3.9 |
| 56-60 | 2.2 |
| 61-65 | 3.4 |
| 66-70 | 1.5 |
| 71-75 | 2.9 |
| 76-80 | 1.7 |
| 81-85 | 0.7 |
| 86-90 | 1.0 |

*408 particles counted.

## FIGURE LEGENDS

Fig. 1 Schematic of Open-end composite spinning apparatus

Fig. 2 Two-slurry Vortex tube Spinning assembly

Fig. 3 Close-up of Spinning assembly and the No. 2 Spinning head

Fig. 4 Spinning head No. 1

Fig. 5 Spinning head No. 2 with the short barrel, "A" barrel and "B" barrel.

Fig. 6 Mats of glass yarn spun from β E-glass (PY-23). The solid circle is a 1/4" dot.

Fig. 7 Close-up of glass yarn (PY-23). The solid circle is a 1/4" dot.

Fig. 8 Single strands of glass yarn spun with variable twist: PY-23 (upper) and PY-15 (lower)

Fig. 9 Samples of yarn wound on drums using first, only the wrapping slurry tank [CS-9 (Fortisan rayon), CS-13 (Acrilan), and PY-15 (β E-glass)] and second the two slurry tanks [PY-1 (glass/triacetate rayon) and PY-27 (glass/triacetate rayon)].

Fig. 10 Yarn (PY-26) with a core of glass wrapped with triacetate rayon (top and middle). The solid circle is a 1/4" dot. In the bottom picture the core is shown after the rayon was burned off.

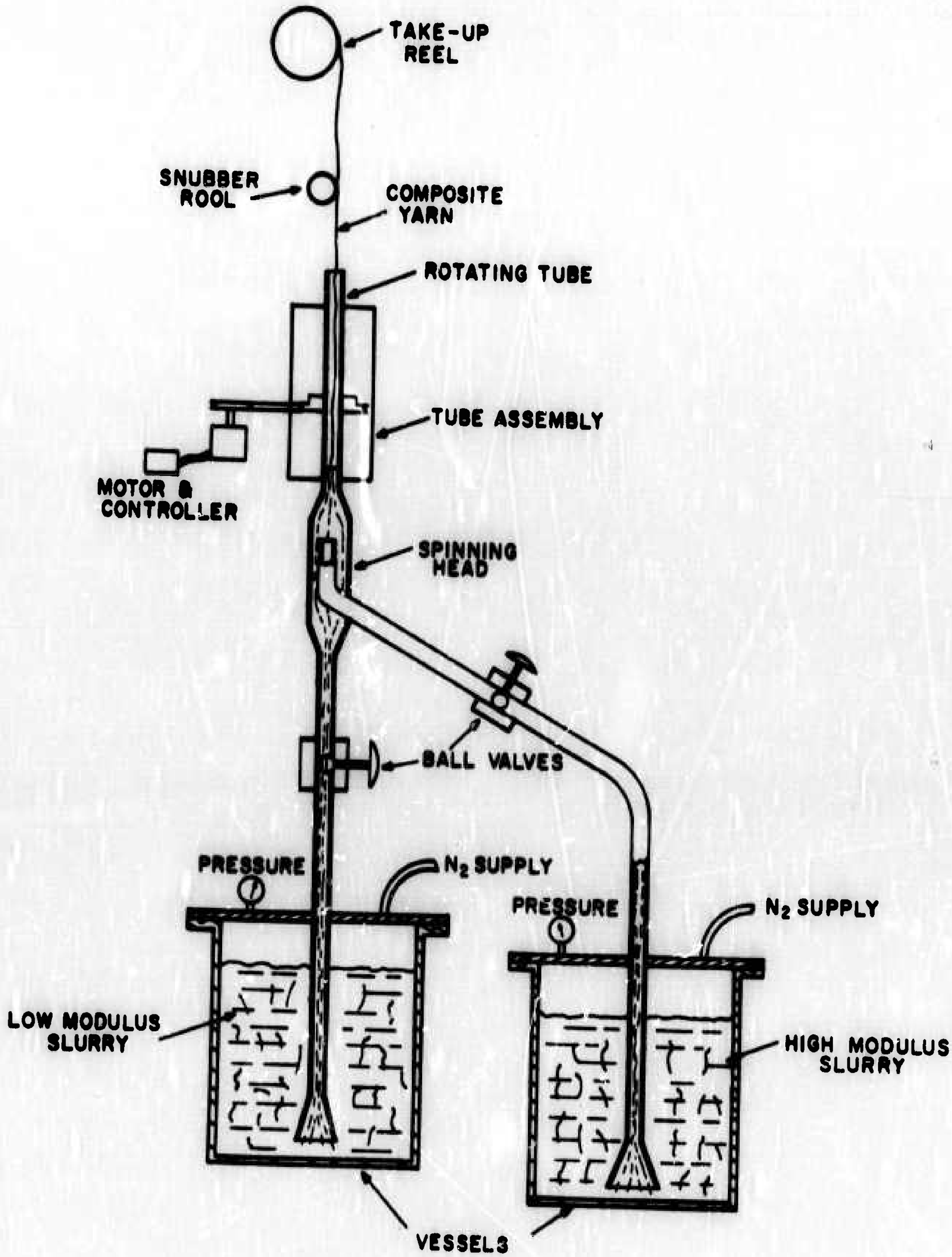
Fig. 11 Two-component glass/triacetate rayon yarn (PY-12) with a volume fraction glass = 0.06.

Fig. 12 Two examples [PY-1 (top) and PY-9 (bottom)] of strands of yarn before and after burn off of the triacetate rayon.

Fig. 13 Mat of 100% glass yarn (PY-20) spun with glass in the core and wrapping slurries. The core fiber was red E-glass and appears as faint horizontal streaks. Spinning was carried out with negligible twist applied to the wrapping fibers.

Fig. 14 Two examples of 100% glass spun using glass in the core slurry and wrapping slurry. The solid circle in a 1/4" dot. The yarns are PY-17 (top) and PY-21 (bottom).

Fig. 15 Strands of yarn (PY-14) exhibiting "puffs" which occurred when the flow rates from the two slurry tanks were approximately equal. The solid circles are 1/4" dots.




SCHEMATIC OF OPEN-END COMPOSITE SPINNING APPARATUS

FIG. 1

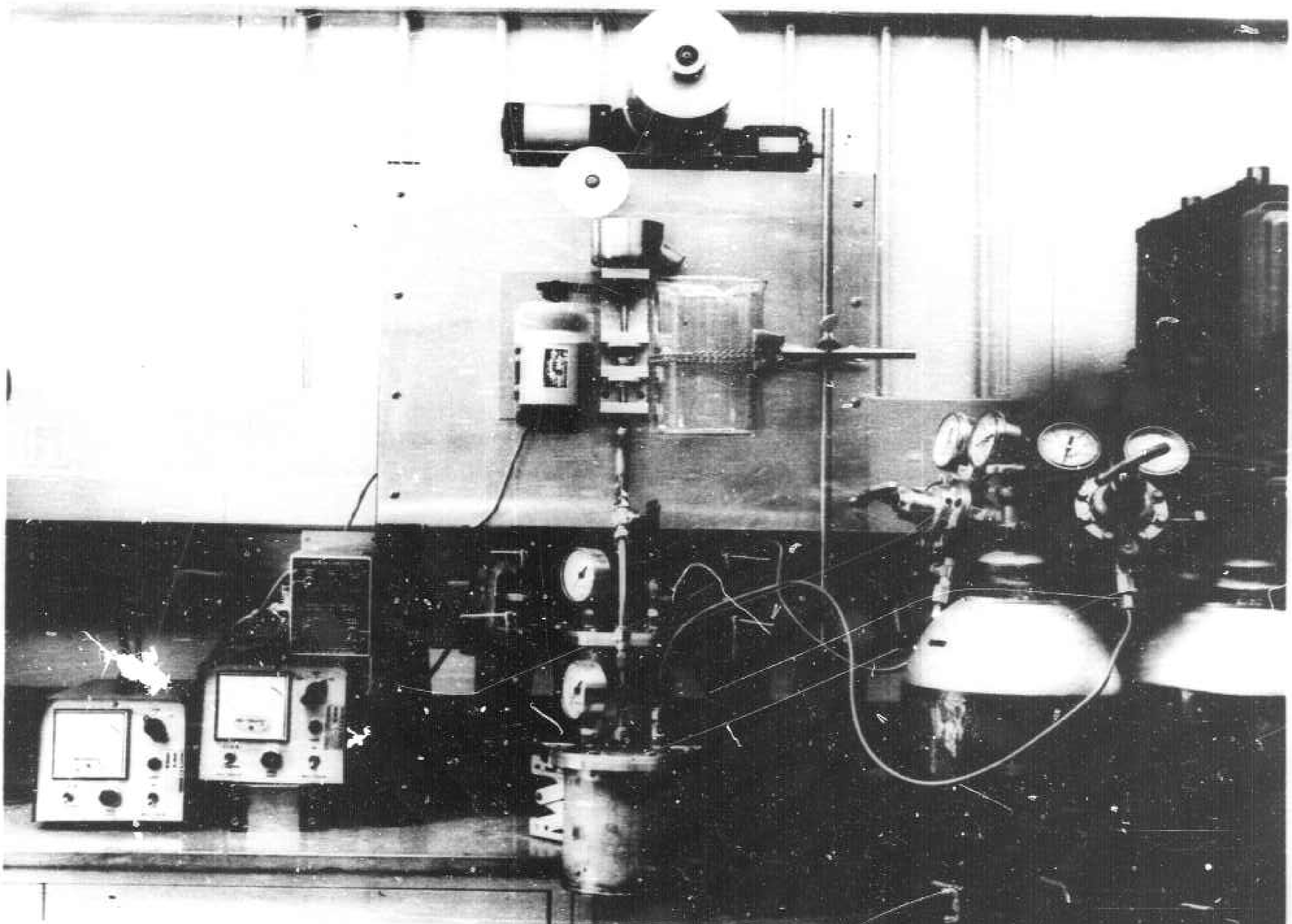


Fig. 2

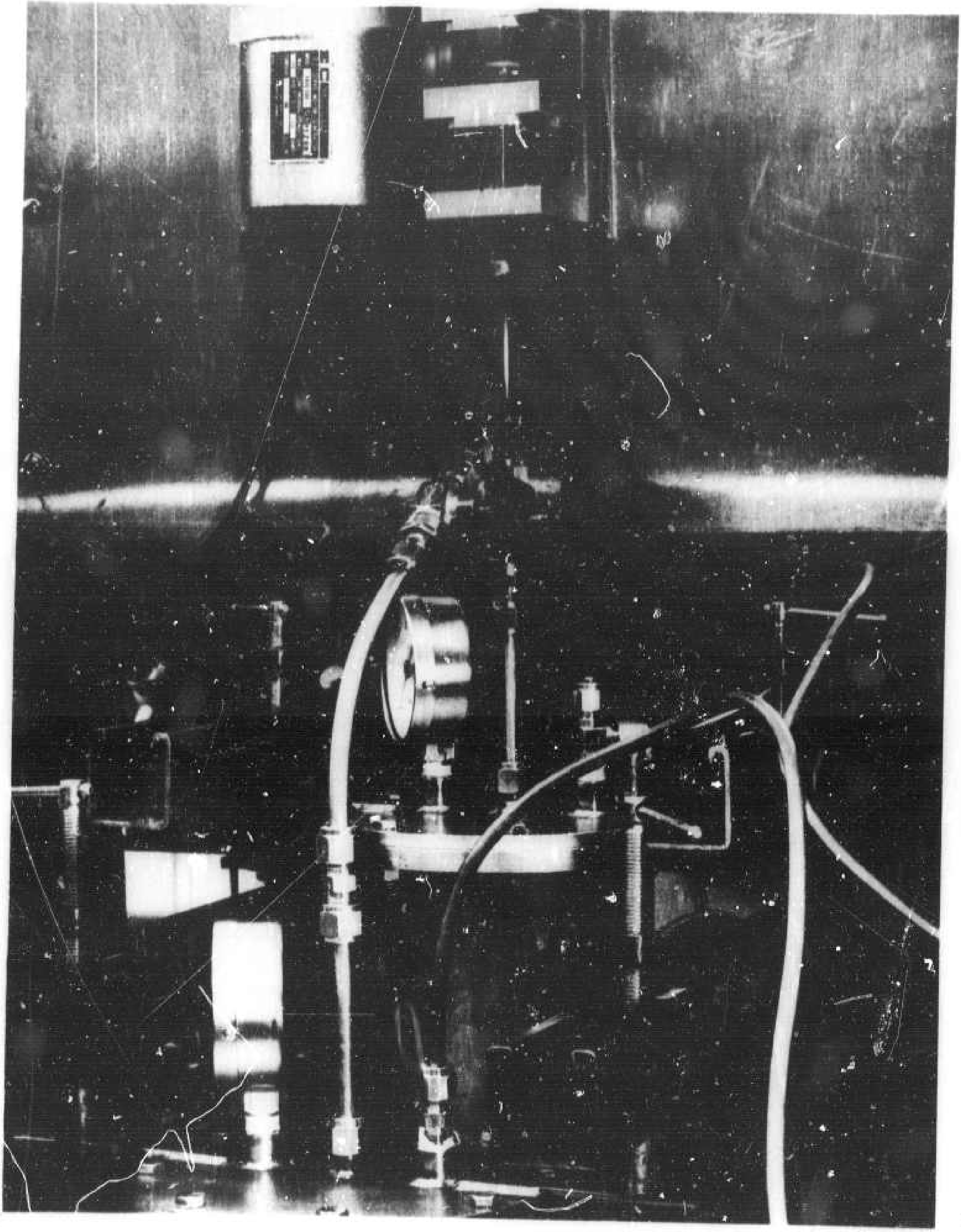
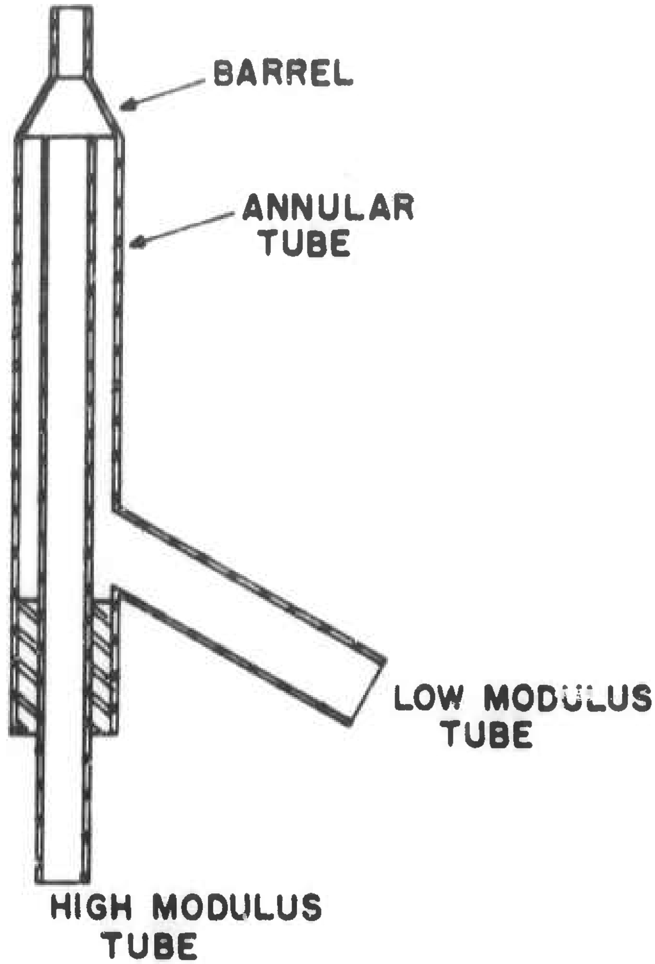
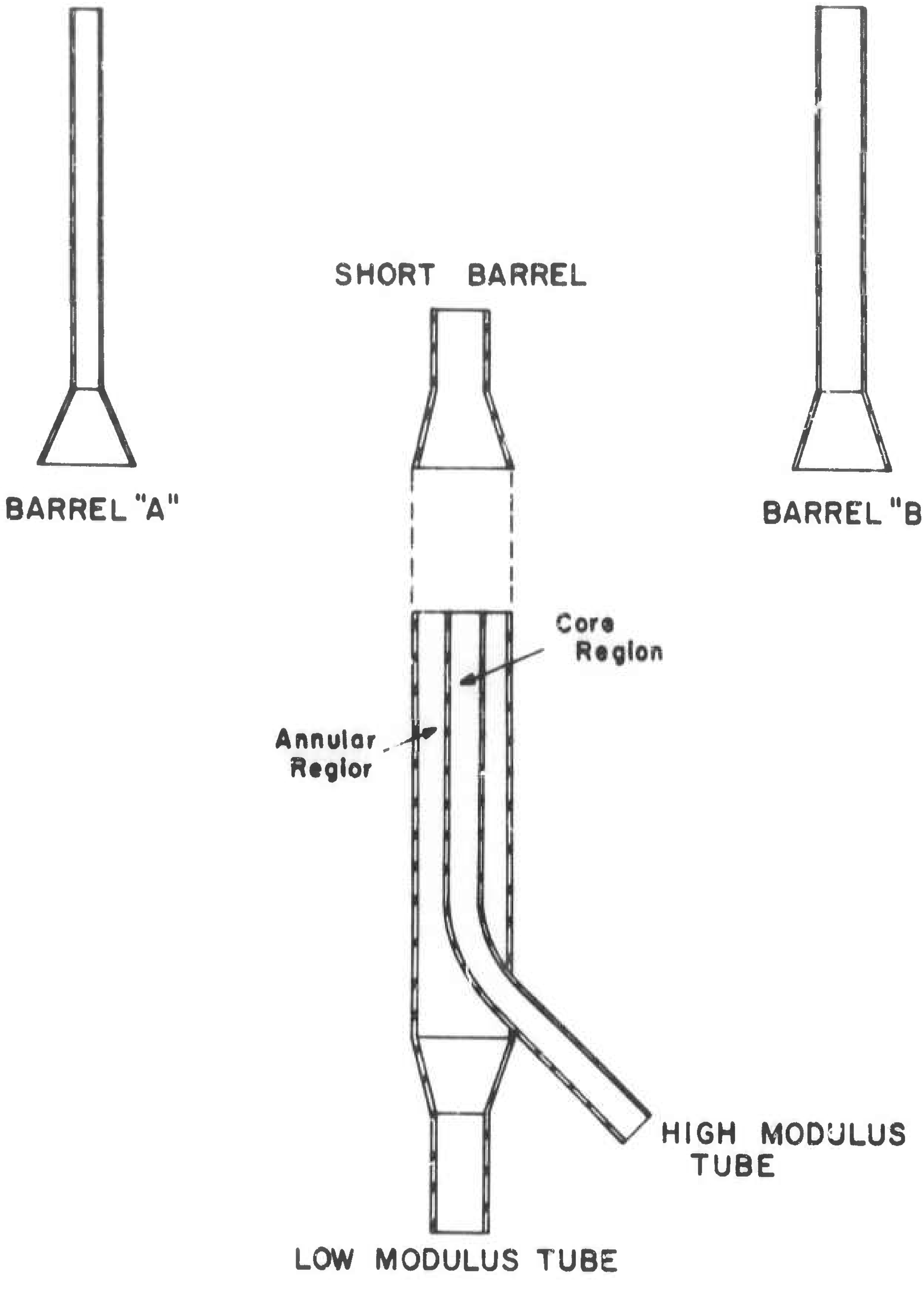


Fig. 3




SPINNING HEAD No. 1

FIG. 4




SPINNING HEAD No. 2

FIG. 5

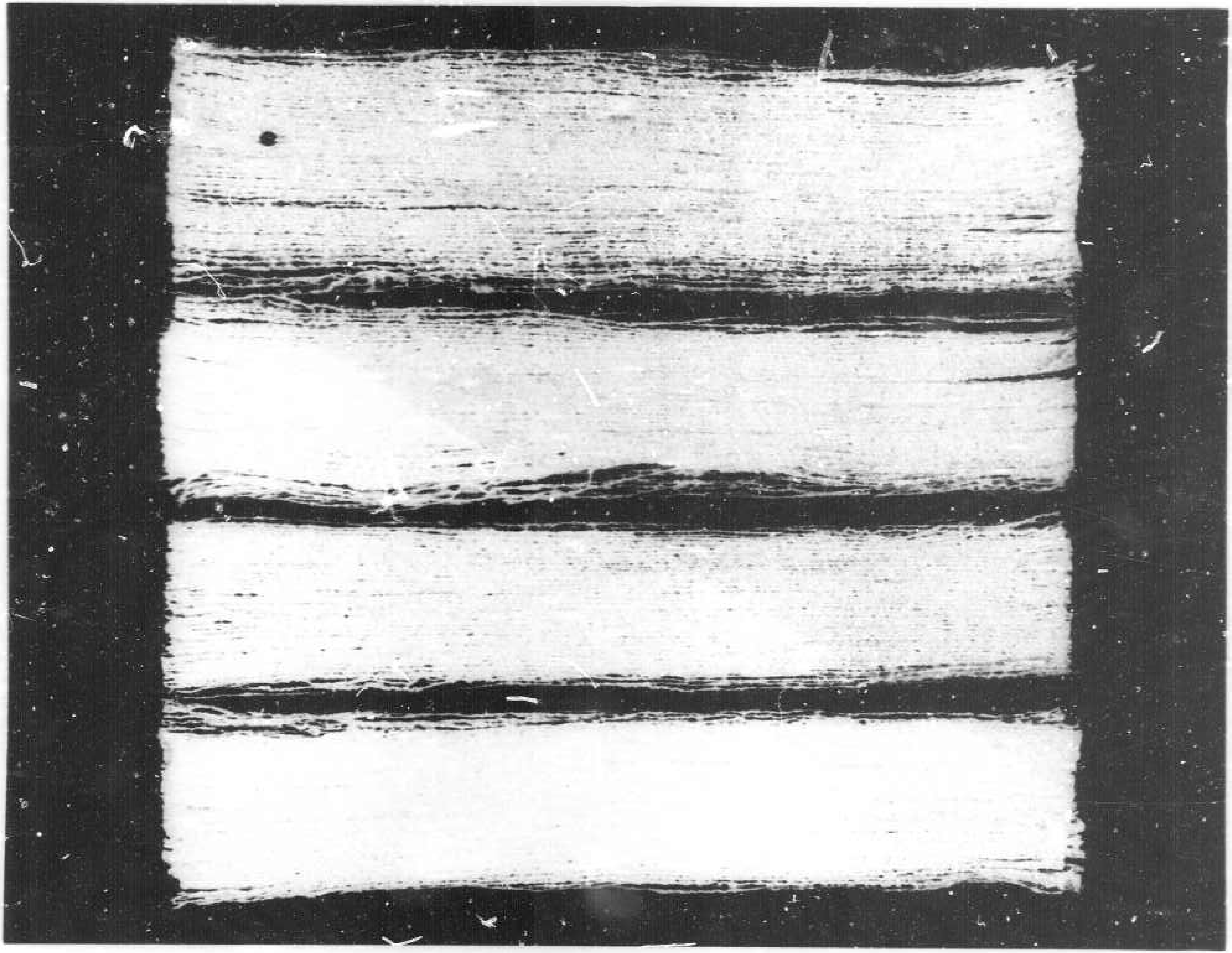


Fig. 6

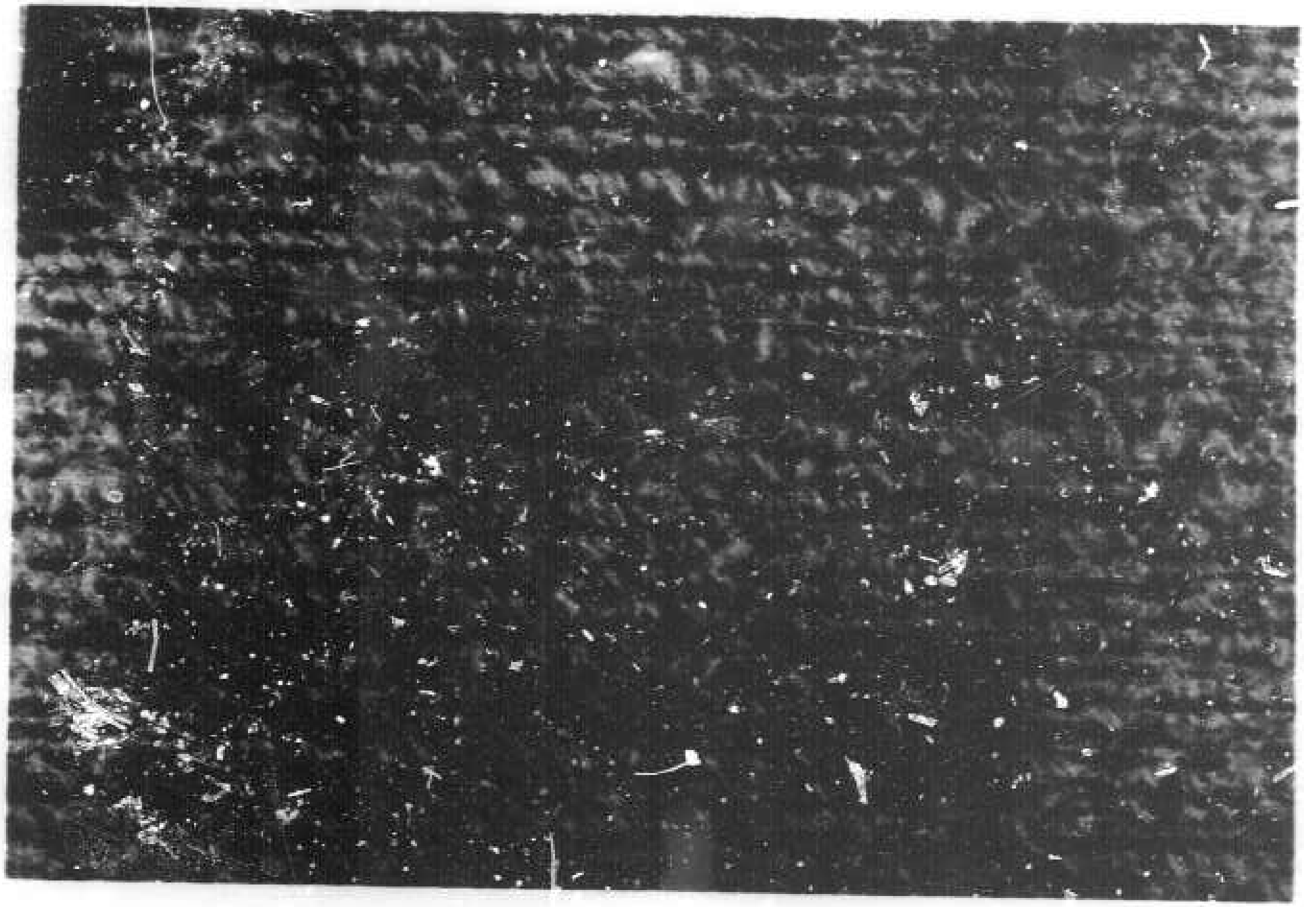


Fig. 7

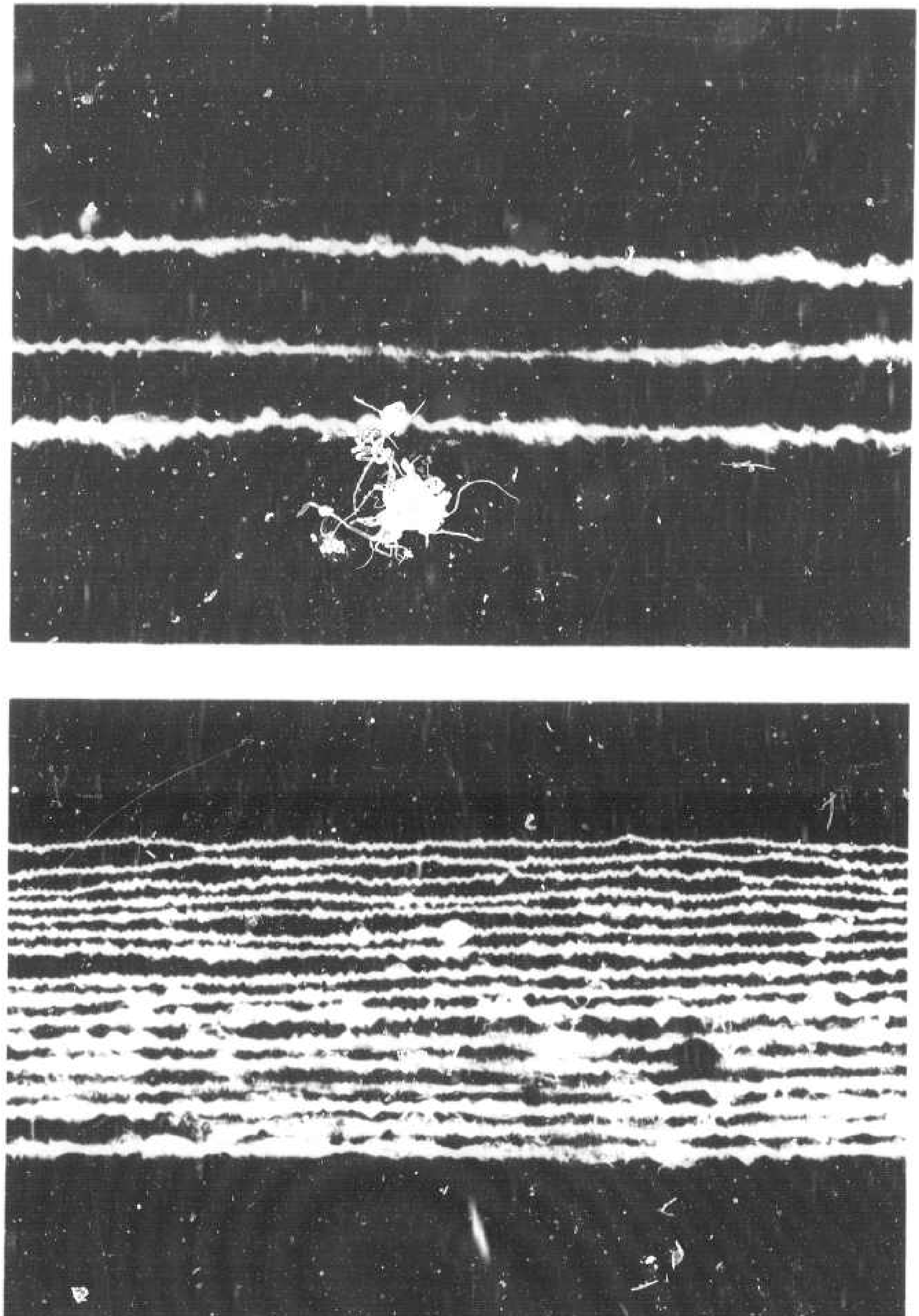


Fig. 8

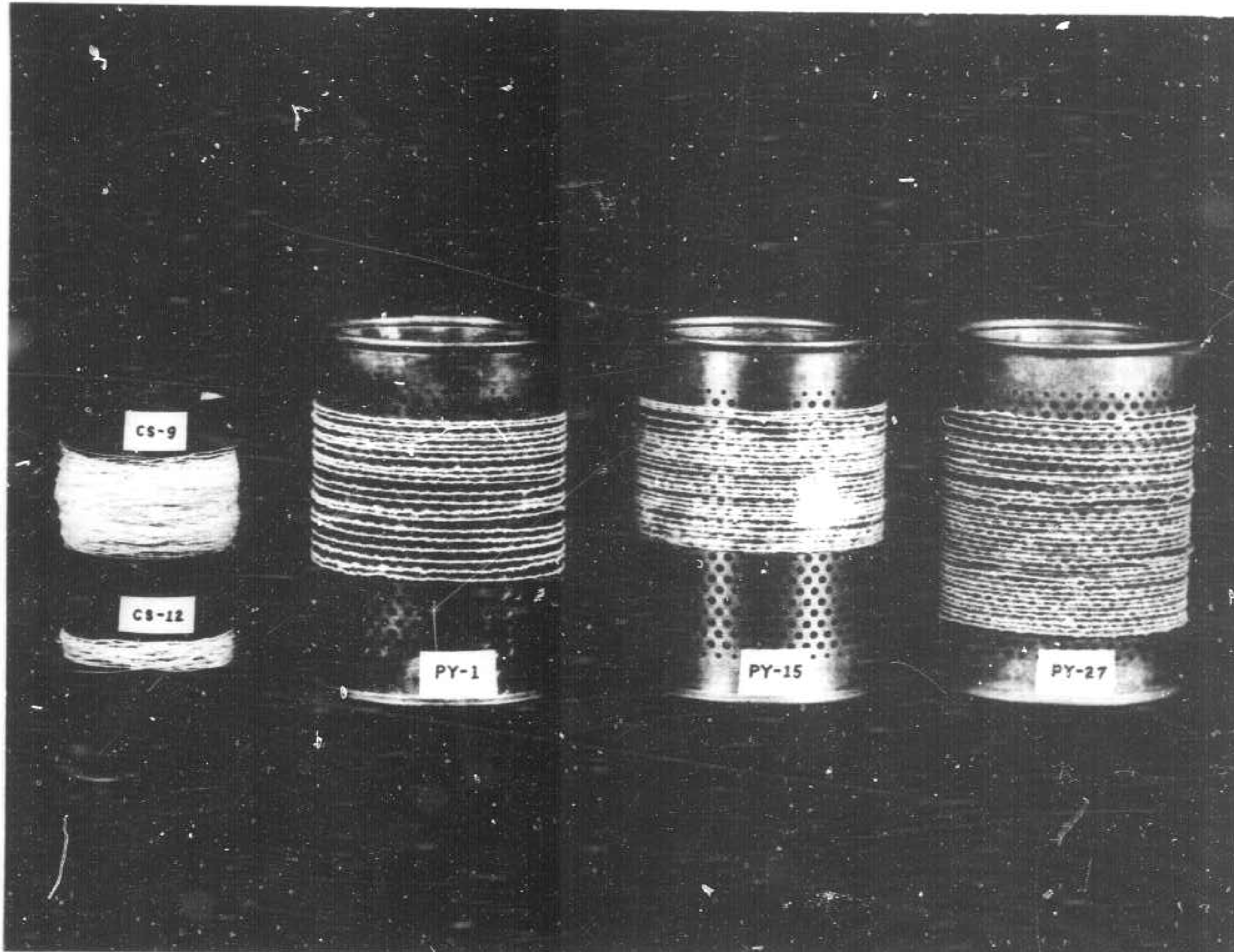



Fig. 9

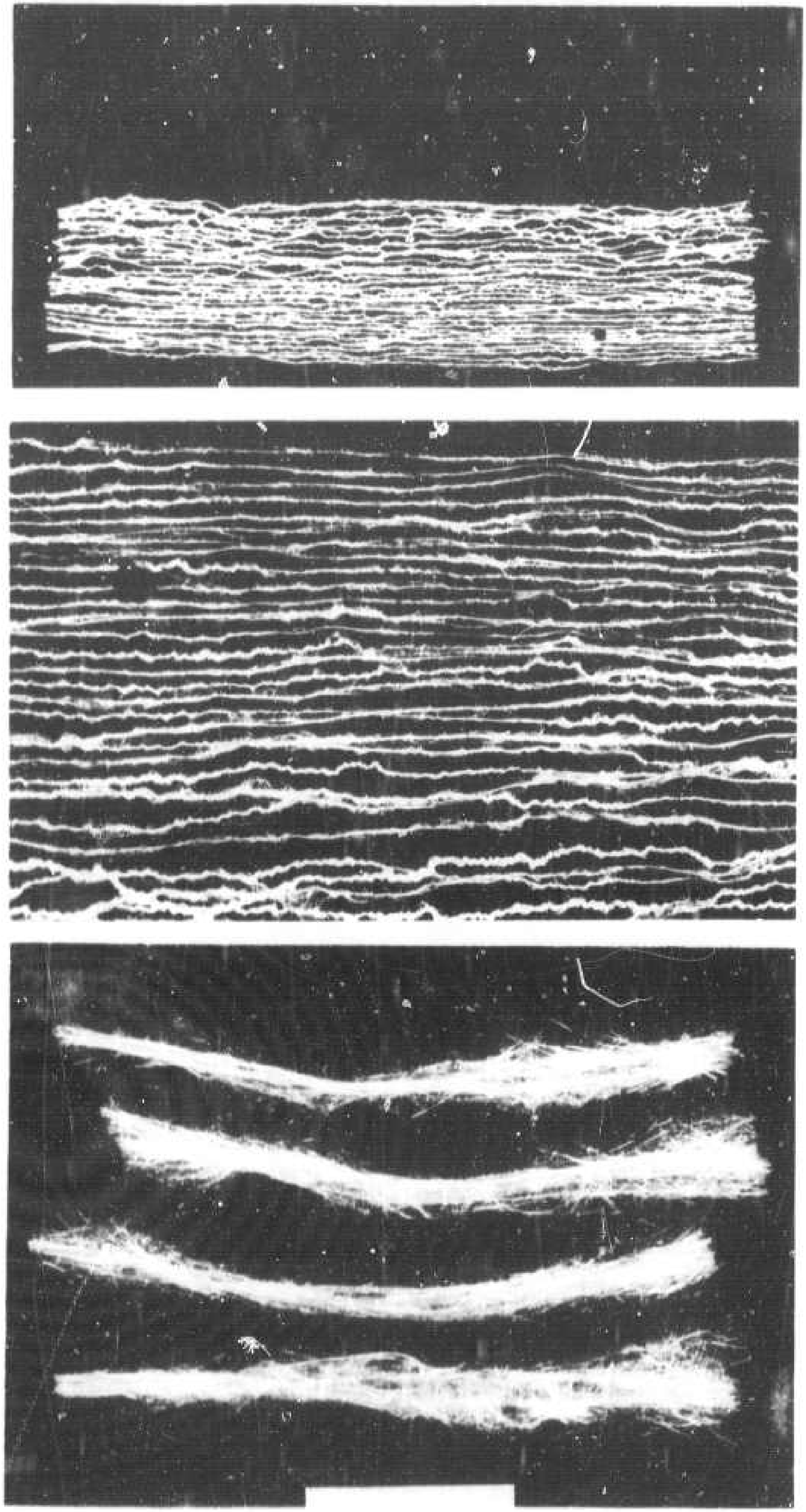


Fig. 10

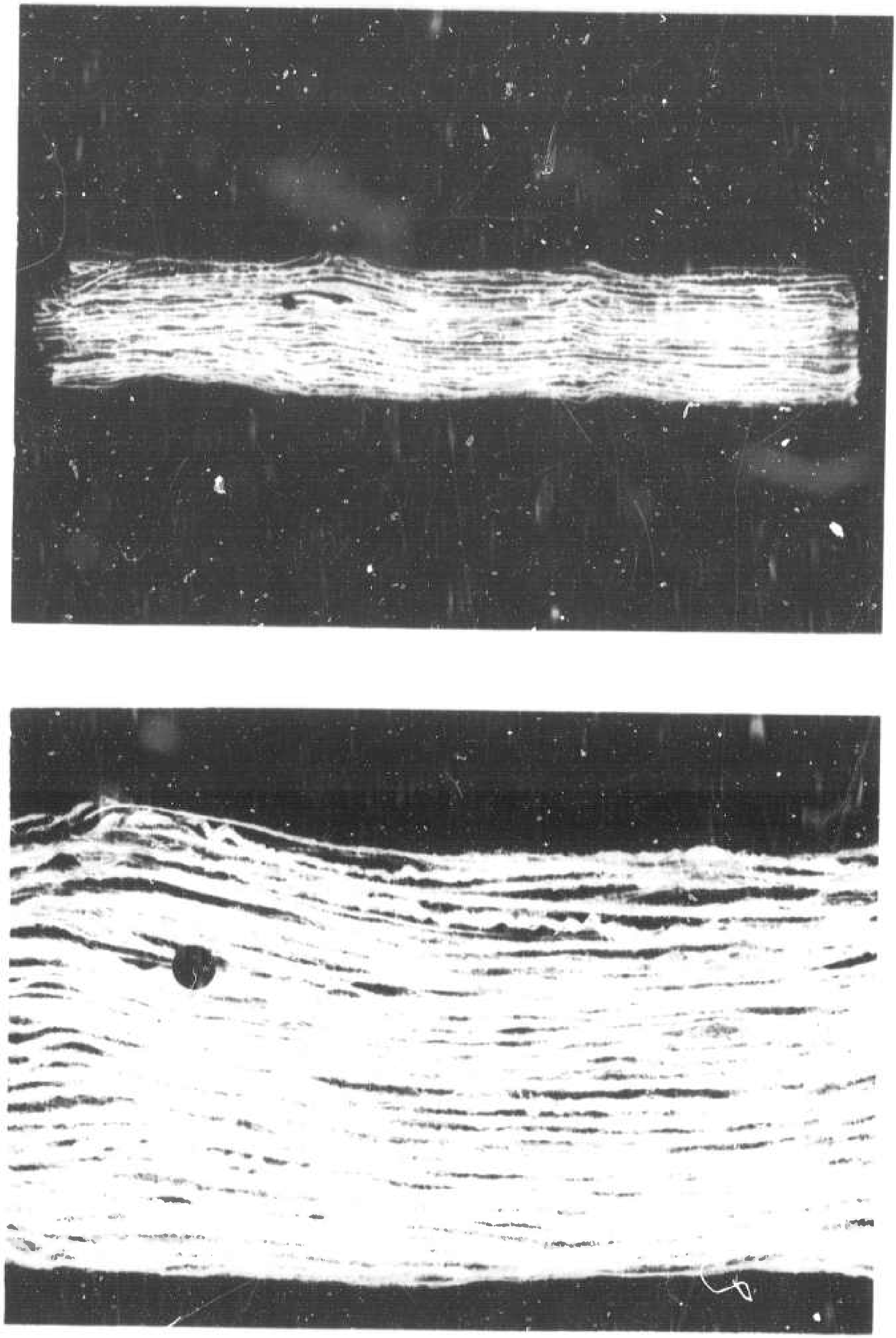


Fig. 11

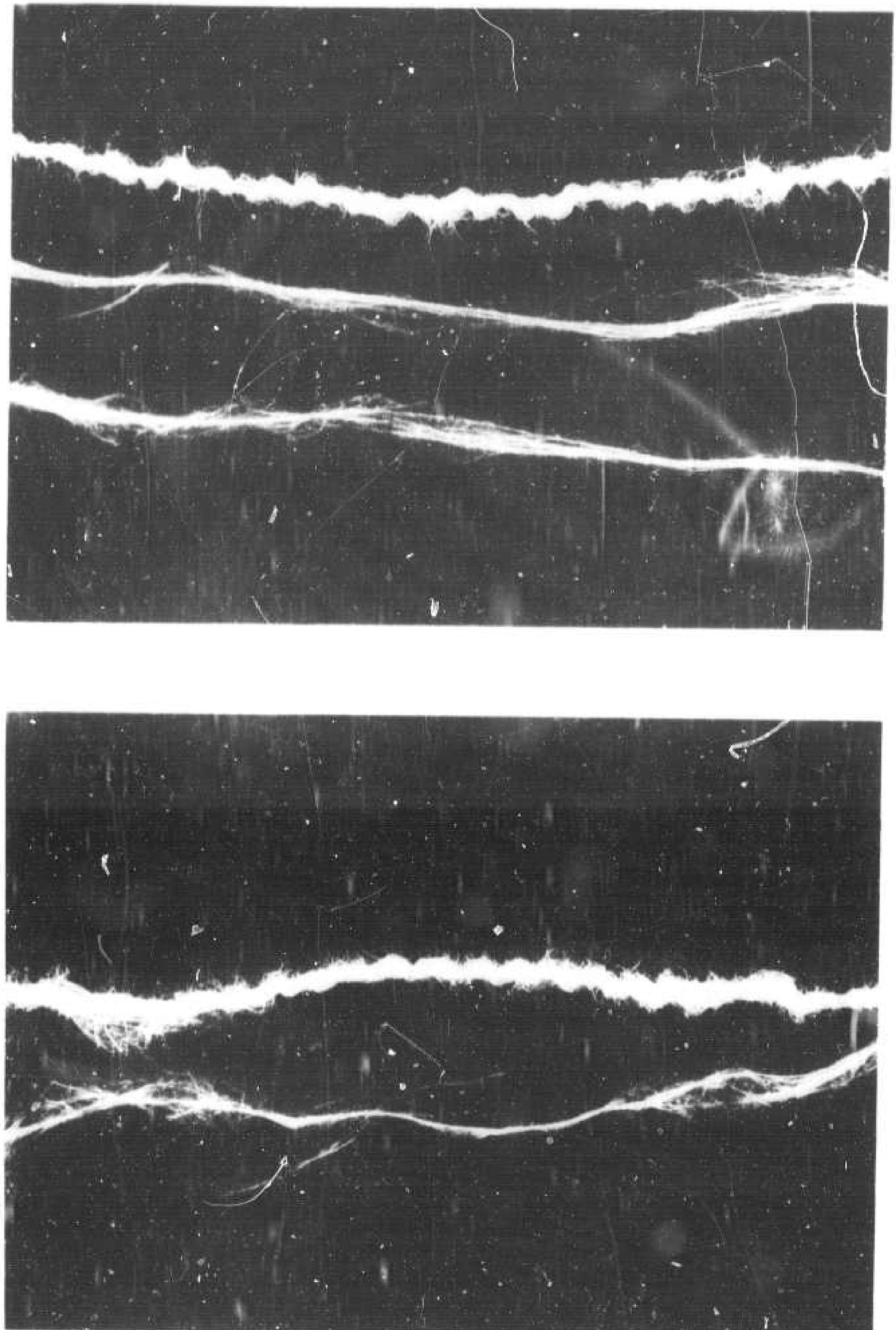


Fig. 12

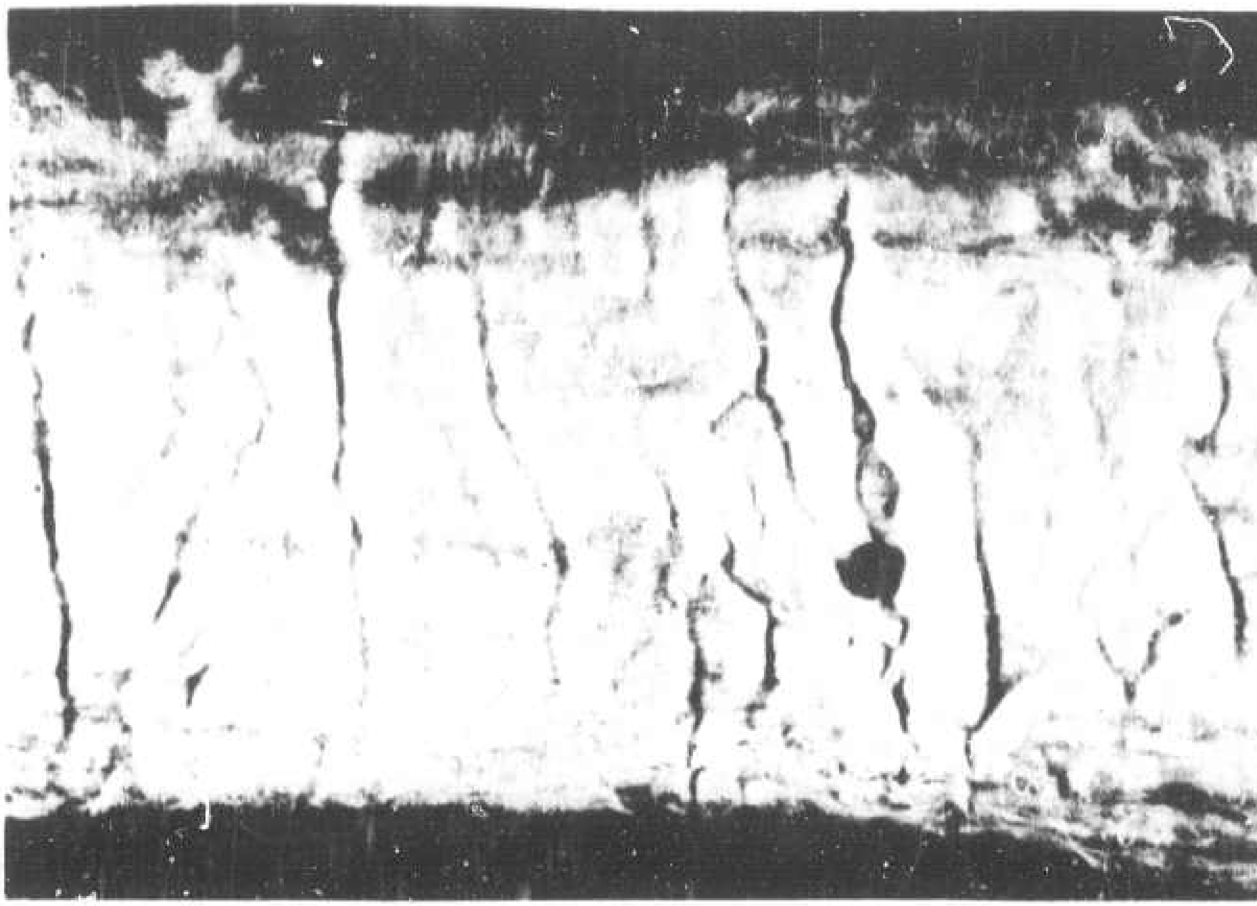


Fig. 13

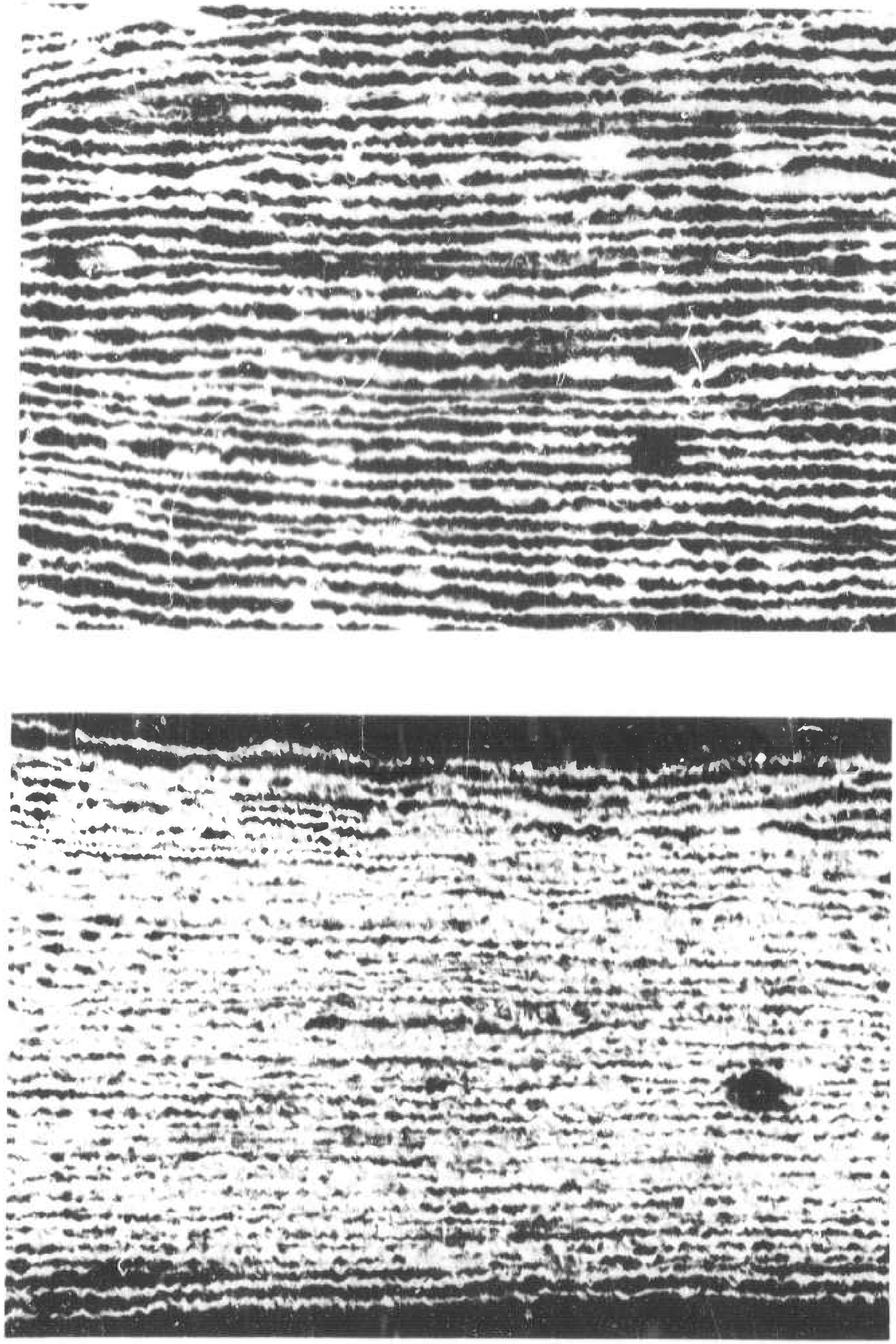


Fig. 14

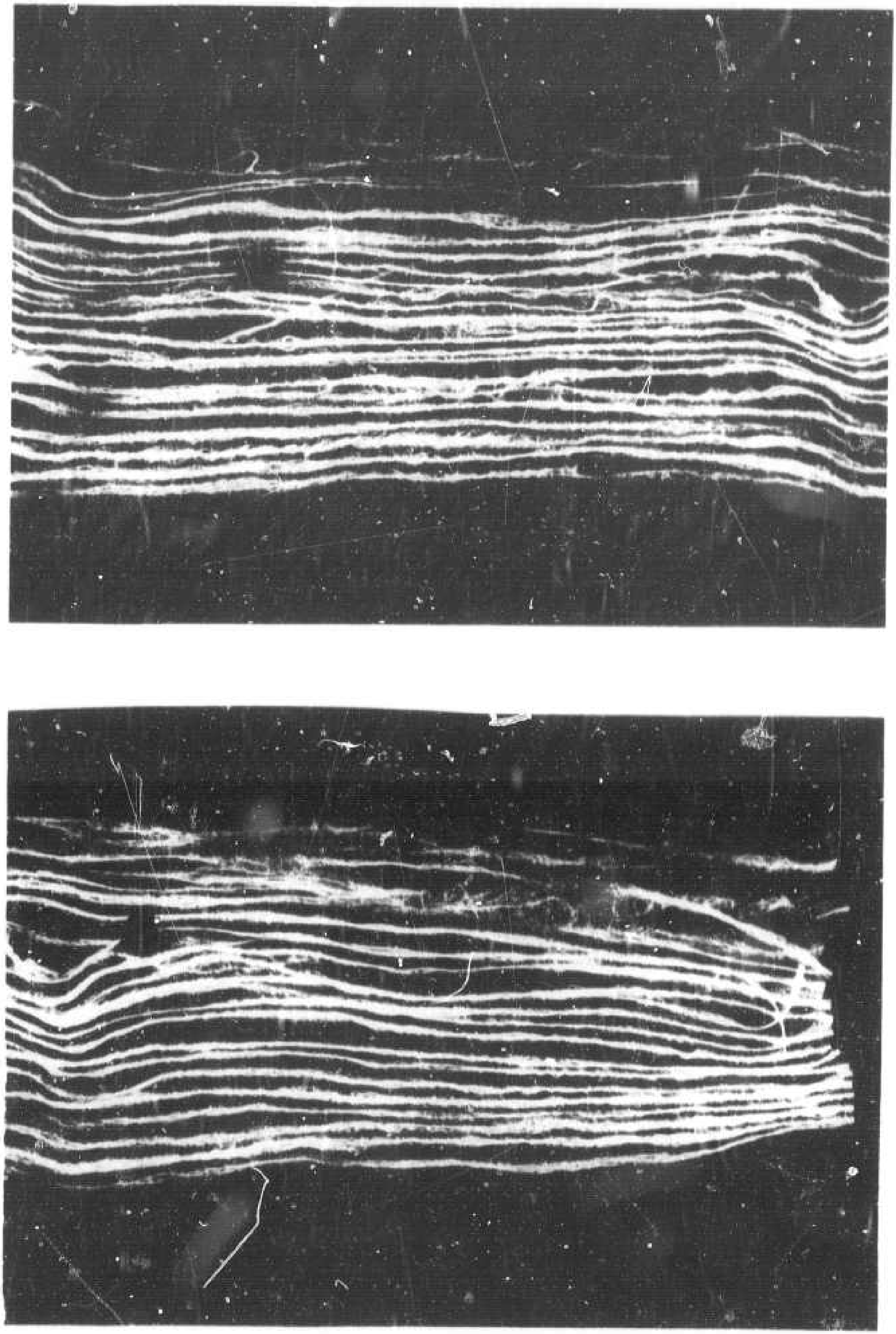


Fig. 15

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13. ABSTRACT

A two-slurry vortex spinning process was developed for spinning a yarn of aligned high modulus core fibers wrapped with helically twisted fibers of the same or lower modulus. Yarn was formed at the entry to the rotating tube of the spinning assembly as the annular fiber suspension twisted around the more viscous core slurry. The rotating tube generated an axial vorticity gradient within the suspension, and the resulting hydrodynamic force twisted the outer fiber layer. Yarn was spuj consisting of: chopped glass in the core and wrapping positions; glass as the core wrapped with synthetic textile fibers; long staple β-silicon carbide whiskers wrapped wigh glass and synthetic fibers. The operating limits for spinning yarn with the apparatus were determined.

Fiber reinforced epoxy composites were formed using yarn spun with the vortex device. The mechanical properties were comparable to values obtained on extruded discontinuous fiber composites.

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| KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| discontinuous fibers | | | | | | |
| whisker fibers | | | | | | |
| glass fibers | | | | | | |
| two-component yarn | | | | | | |
| vortex spinning | | | | | | |
| open-end spinning | | | | | | |
| composites | | | | | | |
| fiber alignment | | | | | | |
| fiber dispersion | | | | | | |
| rotating-tube vortex | | | | | | |